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Assessment of environmental impacts of biogas production using a Life Cycle Approach

Master's Thesis

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Materials and Processes of Sustainable Energetics
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Declaration

Hereby I declare that this master's thesis, my original investigation and achievement, submitted for the master degree at Tallinn University of Technology has not been submitted for any degree or examination.

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LIST OF ABBREVIATIONS AND ACRONYMS

AD	Anaerobic Digestion
AP	Acidification Potential
CH_4	Methane
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
CO_2eq	Carbon Dioxide Equivalent
DM	Dry Matter
D2M	Diesel replacement and 2 million Nm3 yearly output capacity biogas production plants
D5M	Diesel replacement and 5 million Nm3 yearly output capacity biogas production plants
EC	European Commission
EEA	European Environment Agency
EF	Emission Factor
EMEP	European Monitoring and Evaluation Programme
EP	Eutrophication Potential
FU	Functional Unit
GHG	Greenhouse Gas
GWP	Global Warming Potential
IIR	Informative Inventory Report Submitted under the Convention on Long-Range Transboundary Air Pollution
IPCC	The Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment,
LULUCF	Land use, Land-use Change and Forestry
NG	Natural Grass
NH_3	Ammonia
NIR	National Inventory Report Submission to the European Commission
NO_x	Mono-nitrogen Oxides (nitric oxide and nitrogen dioxide)
N_2O	Nitrous Oxide
P2M	Petrol replacement and 2 million Nm3 yearly output capacity biogas production plants
P5M	Petrol replacement and 5 million Nm3 yearly output capacity biogas production plants
Pr2M	Proportional replacement of diesel and petrol fuels according to the proportion of contemporary consumption and 2 million Nm3 yearly output capacity biogas production plants
Pr5M	Proportional replacement of diesel and petrol fuels according to the proportion of contemporary consumption and 2 million Nm3 yearly output capacity biogas production plants
SETAC	The Society for Environmental Toxicology and Chemistry
SO_2	Sulphur Dioxide
UNEP	The United Nations Environmental Programme
VS	Volatile Solids

INTRODUCTION

Estonia's biomethane potential is evaluated to be around 450 million Nm^3, of which grass biomass accounts for over 80%. This distribution of resources is explained by the fact that only a mere one-third of the theoretical total yield of Estonia's grass biomass is used purposefully, while 1.4 million tons in dry weight is unapplied every year. According to the research by Vohu (2015) in case 9.5% of Estonia's aggregate petrol and diesel fuel consumption were replaced by biomethane, the required amount of biomethane would be 109-139 million Nm^3, depending on the fuel type replaced. The European Union (EU) Directive 2009/28/EC (adopted in 2009) on the promotion of the use of energy from renewable sources (RED) holds a mandatory minimum target for the use of fuels produced using renewable energy sources and according to RED should constitute 10% of the total consumption of petrol and diesel fuel in transport by 2020 in each member state.

The goal of current master's thesis was to assess alternative biogas processing routes and single out the most favorable scenario in terms of environmental gain considering Estonia's context of biomethane usage and production. The analysis using a life-cycle approach was carried out based on the scenarios created within the framework of a study *Biomethane production and use as a transport fuel –value chain and implementation proposals* by Vohu (2015) (supervised by Ülo Kask). The latter study aimed to evaluate economic impacts in case of reduction of petrol and diesel fuel consumption as a vehicle fuel and their replacement with biomethane. The presumption of the model calculation was that 9.5% liquid transport fuels (1 TWh) would be substituted by biomethane which, depending on the type of fuel, would replace 90.6 million liters of diesel fuel, or 104 million liters of petrol consumption per year. To execute the goal of the current master's thesis a Life Cycle Assessment (LCA) was conducted following the guidelines set in the ISO 14044:2006 standard.

More specifically, by singling out a scenario that presents minimum negative impacts to the environment, a decision tool was developed for best available practices from an environmental protection standpoint to use in conjunction with the economic analysis of the study by Vohu (2015). Simultaneously, an LCA for the entire production chain enabled to pinpoint the main contributing unit processes to the emission flows.

1. LITERATURE OVERVIEW

1.1 Background and legal context

According to the EU RED Directive 2009/28/EC the percentage of renewable energy in the energy consumption of the EU should be increased by 20%, energy efficiency improved by 20%, and greenhouse gas emissions reduced by 20% by the year 2020. The directive also holds a mandatory minimum target for the use of fuels produced using renewable energy sources and according to RED should constitute 10% of the total consumption of petrol and diesel fuel in transport by 2020 in each member state. The target is binding for all EU countries and states that production of renewable fuels should be consistent with sustainable development and must not pose a threat to biodiversity (Directive 2009/28/EC). Estonian transport sector greenhouse gas (GHG) emissions were 2 241.92 Gg CO_2eq (carbon dioxide equivalent) in 2013, with a share of 10.5% of the total GHG emissions generated on the territory of Estonia in that same year (NIR 2016).

In line with the RED directive, Estonian government aims to increase the use of renewable energy in the transport sector to 10% by 2020, with plans to support demand by foreign imports if necessary but keeping the focus on domestic production. To achieve this objective, according to the pronouncements in the local media by the government officials in 2015, it is planned to utilize the unused grass growing on hundreds of thousands of hectares of Estonian agricultural lands to produce biomethane and open at least 20 biogas filling stations (European Biogas Association, 2015).

The interest in use and production of biomethane is steadily increasing in many European countries, as many studies have concluded biomethane to be one of the most sustainable biofuels available today. Important advantages of biomethane are, that it can be produced from several different types of feedstock, including waste and agricultural materials and in many cases the possibility to use digestate as fertilizers, thus enabling the recycling of nutrients. Nevertheless, like with implementation of any other new technology in society, various types of measurements are in need to safeguard the most efficient introduction of biomethane. Comprehensive analysis and planning of regional biomass resources and of available technology together with the evaluation of environmental impacts, allow developing sustainable and financially viable biomass harnessing and energy production (Kask et al. 2012).

1.2 Life Cycle Assessment

A pioneer institution in establishing generalized guidelines for conducting an LCA was the Society of Environmental Toxicology and Chemistry (SETAC). In their *Code of Practice*, the definition of LCA is as followed: “Life Cycle Assessment is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials used and releases to the environment; and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing, extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal” (Zbicinski et al. 2006).

The history of LCA reaches back to the 1970s. The early successors of the LCA were methods such as integral environmental analysis, ecobalances, resource and environmental profile analysis etc., which fed into the LCA method around 1990. In 1997 the first standard for LCA, ISO 14040 with the latest revision in 2006 resulting in the two core standards ISO14040 and 14044, were published by the International Organisation for Standardization (Wolf et al. 2012; Zbicinski et al. 2006).

A distinction can be made between attributional LCA (aLCA) and consequential LCA (cLCA). An aLCA-modelling approach accounts for the immediate physical flows in a life cycle. CLCA-modelling on the other hand, examines the environmental consequences of change in life cycle and implies that marginal suppliers or technologies are affected and co-product allocation is avoided by system expansion (Ahmadi Moghaddam et al. 2015; Moora 2009).

In order to compile an LCA according to the requirements stated in the ISO 14044:2006 standard (ISO, 2006), one must cover **four stages (**Figure 1.1**)**:

1. define the goal and scope of the study;
2. conduct a life cycle inventory (LCI);
3. assess the impacts based on the inventory data (LCIA); and
4. interpret the results in relation to the objectives of the study.

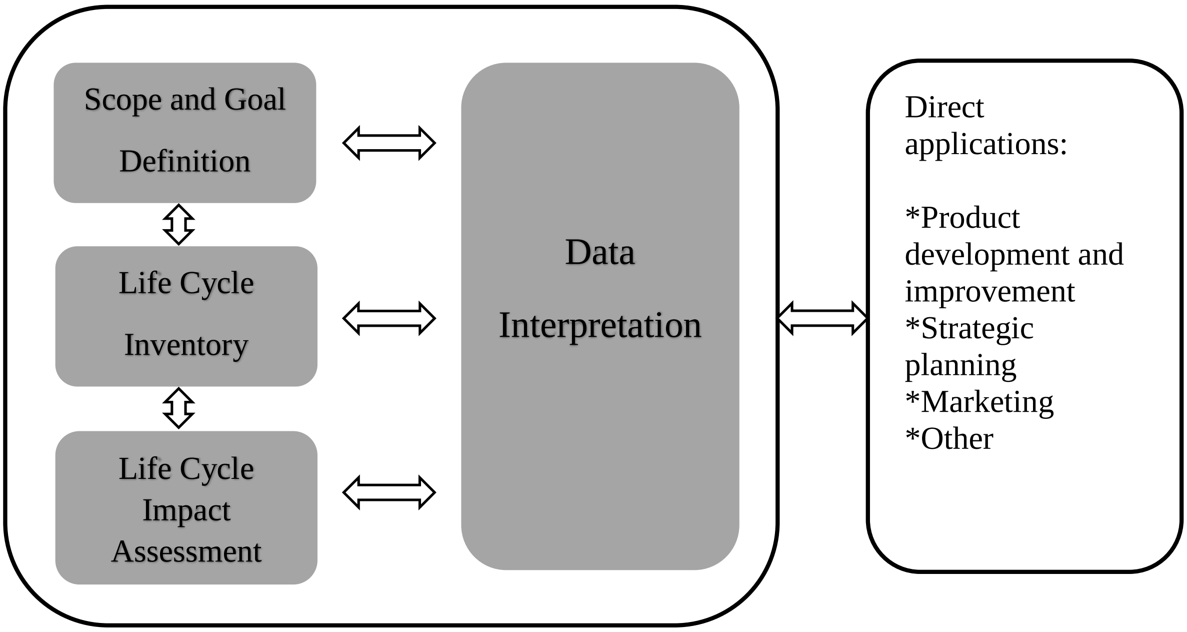

Figure 1.1 Main stages of LCI (UNEP & SETAC 2005)

The impact assessment phase consists of two mandatory actions: classification and characterization. First, it is necessary to disaggregate the LCI results into impact categories, for example global warming, acidification, and human toxicity. Secondly, in characterization part, the potential impact of each emission or resource use is calculated, using certain scientific aggregation factors. For instance, the impact of methane ($CH4_4$) emissions on climate change is estimated using the equivalence (eq) factor of 25 kg CO_2.

The impact indicators considered to be most suitable for describing processes involving agricultural practices and implemented in several other biogas production LCAs are global warming, eutrophication and acidification potentials (Pehme 2013; Moora 2009; Fuchsz & Kohlheb 2015). The relevance of these impact categories for the current master's thesis goal is subsequently explained.

Firstly, global warming is the result of the accumulation of gases, such as CO_2, N_2O (Nitrous Oxide), CH_4 and halocarbons in the atmosphere. The proclaimed consequences of the anthropogenic greenhouse effect include higher global average temperatures, and changes in the global and regional climates (IPCC 2016). In this LCA Global Warming Potentials (GWP) for 100 year time horizon originate from the IPCC Fourth Assessment Report (2007) were implemented: 1 kt CO_2eq for kt CO_2, 25kt CO_2eq for kt CH_4 and 298 kt CO_2eq for N_2O. Secondly, the rate and extent of eutrophication characterized as excessive plant and algal growth due to the increased availability of one or more limiting growth factors needed for photosynthesis, such as sunlight, CO_2, and nutrient fertilizer, has been accelerated by human activities (Schindler 2006). Discharging of limiting nutrients, like nitrogen (N) and phosphorus (P), into aquatic ecosystems (i.e., cultural eutrophication) can have dramatic consequences for drinking water resources, fisheries, and recreational water bodies (Carpenter et al. 1998). Finally, increased acidity in for example terrestrial systems leads to a rise of disintegration of (essential) minerals. Although, to some extent the disintegration of minerals can neutralize acidifying depositions, it also leads to an imbalance of nutrients. More than 95% of the total acidifying emissions are contributed by releases of nitrogen (e.g. NO_x and NH_3) and sulphur (e.g. SO_2) to air (EDIP 2003 2005).

In the third phase of LCA, life cycle impact assessment (LCIA), the LCI results are translated into the related environmental impacts (Hijazi et al. 2016) and the remaining optional LCIA steps are normalization and weighting. Normalization is used to put the estimated impacts in an appropriate context, e.g., by normalizing them to the total impacts in a region or country in a certain timeframe. Weighting can be used by the LCA compilers to decide which impacts are most interesting to them by determining weights of importance to each impact. The final outcome is an aggregation of impacts into a unified environmental impact value (eco-efficiency) that can assist decision making, especially when comparing different alternatives based on several different criteria (Lehtinen et al. 2011). Another voluntary step listed in the ISO 1404:2006 standard is to conduct a sensitivity analysis for the purpose of determining how changes in data and methodological choices affect the results of the LCIA.

On the whole, LCA can be conducted on different levels, so that the final outcome reflects the effort invested in data collection, calculations and consequently the detailing and the precision obtained. To save time and resources it is recommended to start the assessment with a simple screening LCA, and if needed, move forward with a more detailed assessment, which is also relevant in cases the resources for detailed LCA are limited (Moora 2009).

Three main levels of LCA applications can be differentiated (Wenzel, 1998):

1. life cycle thinking (conceptual qualitative assessment of inputs, emissions, etc.);
2. simplified or screening LCA (based on readily available data in databases or screenings, limited data collection); and
3. detailed or full LCA (incorporates quantitative information and complement of a new data inventory).

Basic LCA concept is to model all important types of environmental impacts of the product or a system. In most cases an LCA will often be limited to the environmental impacts, which are quantified using better known methodologies. For example, then due to incomplete data and lack of consensus on assessment methodology, the impacts of toxic chemical emissions and land use are defectively represented in many LCA models (Reap et al. 2008). Typically the majority of LCAs incorporate only global warming, acidification and eutrophication (Moora 2009).

According to ISO 14044:2006 an important characteristic of an LCA is the scope tied to clearly specified and measurable functional unit (FU) of the system studied. The FU has to be in compliance with the goal and scope of the study to provide reference to which the input and output data are normalized. Consequently, comparisons between systems are to be made on the basis of the same function(s) and quantified by the same FU in the form of their reference flows (ISO 2006)**.**

Limitations of LCA

One of the strengths of LCAs is a holistic approach, that takes into account the whole production chain and considers that the emission reductions in some areas, cause an increase in another part of the chain. Conversely, one of the noticeable drawbacks of the LCA, is the subjective choice of the observed systems' boundaries which creates obstacles in the direct comparison of the seemingly similar LCAs (Huttunen et al. 2014).

Admittedly, environmental LCAs convey a number of limitations and is advisable to be complemented by other methods and instruments, depending on the specific interest for the given case. Rather, an LCA only captures those pressures that act via the environment, i.e. emissions to nature and resource use/extraction from nature, but for example does not take into account the direct effect of products on humans, such as the potential health effects (Huttunen et al. 2014).

In the same way, policies focusing mainly on specific environmental benefits, such as decreasing fossil carbon emissions, may create unexpected side effects regarding all-round sustainability. For instance, Germany's experience show that economic incentives for renewable energy production (Renewable Energy Sources Act) which have increased biogas production, are counterpoised by local conflicts related to changing agricultural landscapes, increasing land prices and experienced loss for quality of life (Huttunen et al. 2014)

1.3 Production and use of biomethane as a transport fuel

Biogas is the result of biomass and waste being converted to CH_4,, CO_2 and water in anaerobic conditions by micro-organisms (Figure 1.2). Industrial biogas is generated at sewage treatment plants, landfills and sites with industrial processing industry and at digestion plants for agricultural organic waste (both mesophilic (35 °C) and thermophilic (55 °C)) (Jönsson et al. 2003).

The chemical composition of the biogas is dependent on the source of the raw materials and the technical conditions of the anaerobic digestion. Unrefined biogas consists mainly of CH_4 (40–75%) and CO_2 (15–60%). Negligible amounts of other components e.g. water (H_2O, 5–10%), hydrogen sulfide (H_2S, 0.005–2%), siloxanes (0–0.02%), halogenated hydrocarbons (VOC, < 0.6%), ammonia (NH_3, <1%), oxygen (O_2, 0–1%), carbon monoxide (CO, <0.6%) and nitrogen (N_2, 0–2%) can be found and is advisable to be removed (Ryckebosch et al. 2011).

The effluent of the digester, referred to as the digestate, consists of the bioavailable fraction of plant nutrients found in the feedstock, but also of the more difficultly degradable organic material. Digestate is usually spread directly to crops (Montes et al. 2013).

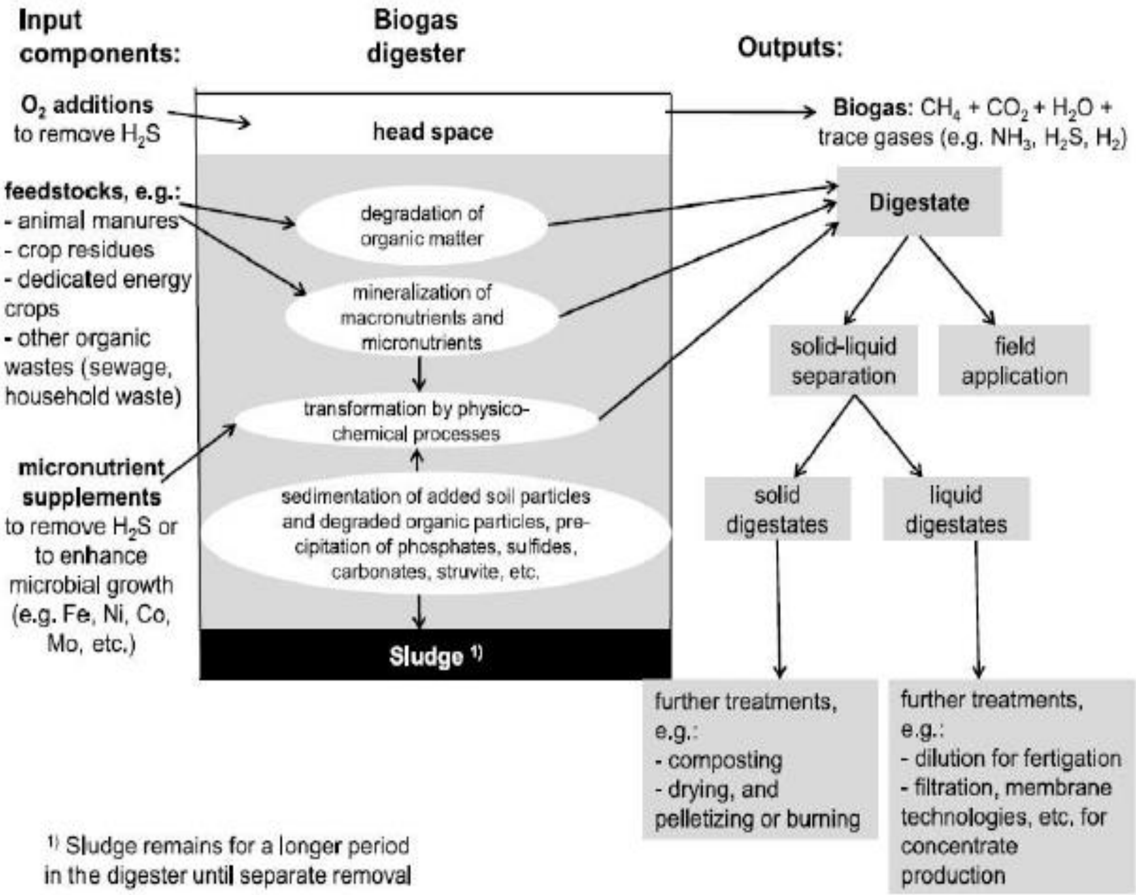

Figure 1.2 Overview of the matter flow and processes during anaerobic digestion and possible treatments of the resulting digestates (reproduced from Möller & Müller, 2012)

Until May 2016, there is no biomethane production in Estonia. Nevertheless, according to Estonian Biogas Association there are 18 operating biogas stations, out of which 5 are working on using agricultural waste as a substrate. Agricultural waste is being processed in the biogas station of Saare Economics in Jööri, in OÜ Aravete Biogas, OÜ Tartu Biogaas in Ilmatsalu, OÜ Vinni Biogaas in Vinni and OÜ Oisu Biogaas in Oisu. In the future, biogas stations are also planned to be constructed in Põlva, Torma and Loole (Baltic Biogas Bus 2011).

Estonia's biomethane potential is evaluated to be around 450 million Nm^3 (Table 1.1), of which grass biomass accounts for over 80%. This distribution of resources is explained by the fact that only a mere one-third of the theoretical total yield of Estonia's grass biomass is used purposefully (Figure 1.3), while 1.4 million tons in dry weight is unapplied every year. According to the research of Vohu (2015) in case 9.5% of Estonia's aggregate petrol and diesel fuel consumption were to be replaced by biomethane, the required amount of biomethane would be 109-139 million Nm^3, depending on the fuel type replaced.

Table 1.1 Estonian biomethane potential by raw produce source (Vohu 2015; Oja 2013)

Raw produce source	**Biomethane potential million Nm^3/year**	**Percentage**
Herbaceous biomass from agricultural lands	375	83.3%
Agricultural waste	44	9.8%
Industrial waste	17	3.8%
Biogas from landfills	9	2.0%
Other waste (sludge, biowaste)	5	1.1%
Total	450	100%

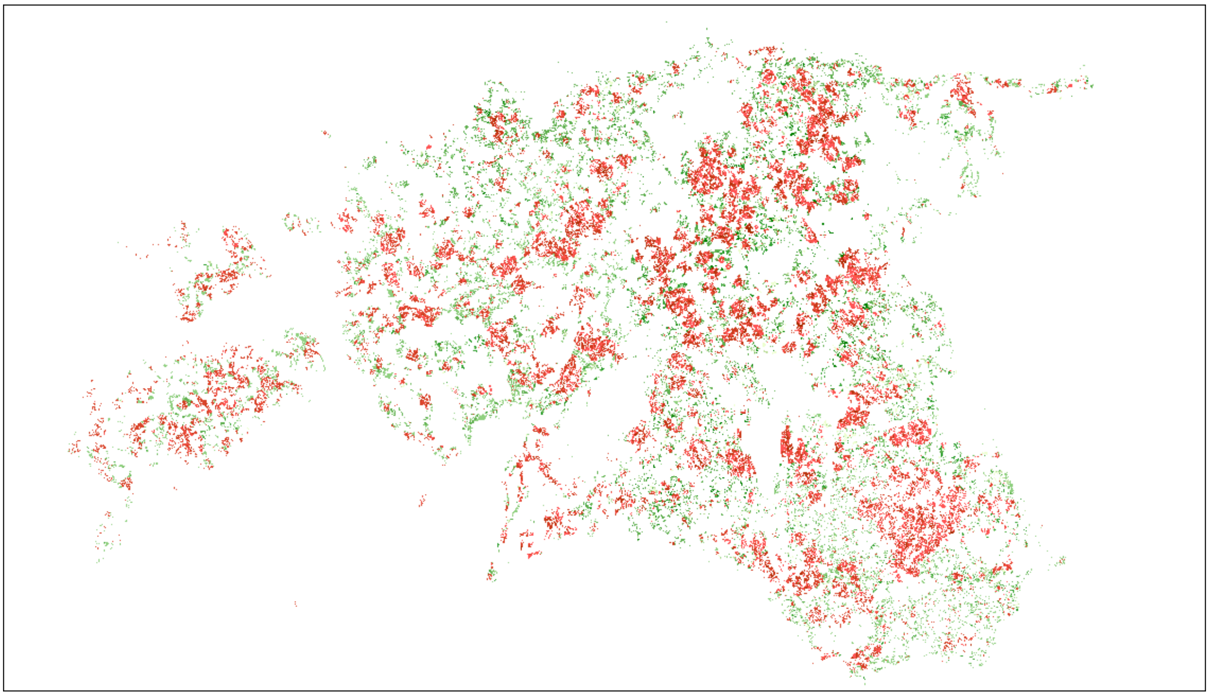

Figure 1.3 Exploitation of Estonian grasslands (red-in use; green-underused)(Vohu 2015)

The main conclusions of the master's thesis by Vohu (2015) where he analyzed the biomethane resources deployment of Estonia were, that the most economically efficient way of using biomethane is when it is produced in large production units as the production of biomethane yields considerable economies of scale. Production costs indicated a promising decrease by 14% across the entire value chain assuming the output grew from 2 to 5 million Nm^3/p.a. and over. Additionally, the analysis of logistics costs showed the most economical way of transporting biomethane within a distance of 50 km to be the transport of grass biomass as a biomethane substrate. Consequently, in Estonia this would mean that around 80% of the country should be within a reasonable distance of natural gas pipes and that emphasis should be put to the establishment of stations connected to the pipe network.

One of the main deductions drawn from Vohu's (2015) research was that the most economically feasible scenario would be the one assuming replacement of petrol with biomethane (assuming CNG replacing petrol at a lower replacement coefficient than diesel fuel).

Vehicle use

Exploiting of biogas in the transport sector is a promising technology with important socio-economic benefits. Biogas is used as vehicle fuel in several European countries, such as Sweden, Germany and Switzerland, with an ongoing growth in the number of private cars, public transportation vehicles and trucks using biomethane as a transport fuel. Biomethane can be used in the same way and by the same vehicles as natural gas. Moreover, a sprawling number of European cities are headed towards converting their regular buses with biomethane driven ones (SEAI 2012).

A prerequisite for using biomethane in vehicles is the vehicle to contain a designated compressed natural gas (CNG) tank and that these vehicles are fueled by CNG or compressed biomethane (CBG). One technical solution for this involves the use of dedicated engine, which is a spark ignition (SI) engine optimized for running on compressed CH_4. Another possible technical solution to use biomethane in a vehicle is a bi-fuel SI engine modified to operate on CH_4 but which maintains the ability to run on petrol as a back-up fueling system. The third possibility is the existence of a dual fuel engine, which is a compression ignition (CI) engine, modified to operate on a mixture of CH_4 and diesel, which is employed for heavy vehicles (Kask et al. 2012).

New CNG passenger cars regularly have bi-fuel engines, equipped with a tank for conventional fuel and with a tank for compressed CH_4. Several auto manufactures have bi-fuel vehicles on the market, e.g. Fiat, Mercedes, Opel, Subaru, Volkswagen and Volvo. However, it is technically possible to supply an existing petrol vehicle by retrofit in order to use CH_4 fuel as well (Kask et al. 2012).

Upgrading of biogas into biomethane

It is feasible to distribute biogas through the existing natural gas networks and use it for the same purposes as natural gas including to be used as renewable vehicle fuel. Before delivering into the natural gas grid or to utilizing as vehicle fuel, biogas is upgraded to biomethane, which means all contaminants as well as CO_2 are removed and the content of CH_4 is increased from 50-75% to more than 95%. As small amounts of CH_4 are also removed along with the removal of CO_2 from the biogas, it is important to minimize the possibility of CH_4 slip, for both economic and environmental reasons. The most widespread methods for removing CO_2 from biogas are absorption (water scrubbing, organic solvent scrubbing) and adsorption (pressure swing adsorption, PSA). Less common methods used are membrane separation, cryogenic separation and process internal upgrading (currently under development) (SEAI 2012).

1.4 Environmental effects of biogas production and relevant impact categories

The existing studies (Pehme 2013; Heinsoo et al. 2010; Melts 2014) carried out in Estonia on environmental impacts of biogas production, have generally drawn positive conclusions about using unutilized biomass from natural grasslands. An LCA of co-digestion with natural grass and dairy slurry conducted by Pehme (2013), indicated significantly lower contribution to impact category Global Warming, but increased emissions for Aquatic Eutrophication and Acidification impact categories compared to the reference scenario. The study also suggested that energy grass should only be used as a substrate for anaerobic digestion (AD) in case the land used for producing the grass could not be cultivated for other (food or feed) purposes (e.g. using fields where conditions are not suitable for feed/food production) (Pehme 2013).

The research lead by Heinsoo et al. (2010) investigated the potential of Estonian semi-natural grasslands for bioenergy production by using the biomass yield from semi-natural grasslands, concluded that it is possible to promote both the sustainable management of semi-natural grasslands and the achievement of nature conservation goals. Researcher Melts (2014) came to a similar conclusion in his doctoral thesis about using biomass from semi-natural grasslands.

2. MATERIALS AND METHODS

2.1 Goal and scope of the study

The goal of the current master's thesis was to conduct an environmental impact assessment of the scenarios created within the framework of *Biomethane production and use as a transport fuel ‒value chain and implementation proposals* by Vohu (2015).

More specifically, the aim was to determine an optimum scenario for the production and use of biomethane as a transport fuel at the same time reducing the consumption of petrol and diesel as a vehicle fuel. By singling out a scenario that presents minimum negative impacts to the environment, a decision-aid tool for best available practices from an environmental protection standpoint was created to be used in conjunction with the economic analysis by Vohu (2015).

To execute the goal of the master's thesis an LCA was conducted following the guidelines set in the ISO 14044:2006 standard. The end product of the examined process, was the biomethane substituting liquid diesel and/or petrol fuels. 1 TWh was chosen to be the FU, to which all the relevant environmental effects were referred to.

2.1.1 System overview

The scenarios analysed in this LCA are in more detail described by Vohu (2015). The modelling covered three theoretical substitutions made in the fuel market depending on the type of fuel replaced:

- petrol replacement (P);
- diesel replacement (D); and
- proportional replacement (Pr) of both fuels according to the proportion of contemporary consumption.

Two yearly production output capacities of a biomethane production plant comprise a basis in the biomethane production modelling:

- 2 million Nm^3 yearly output (2M); and
- 5 million Nm^3 yearly output (5M).

The described assumptions were combined into six (2x3 criteria) scenarios representing the economic impacts of the substitutions of the fossil transport fuels. The same input used in the economic impact assessment were used to derive the activity data needed to assess the environmental impacts using a life cycle approach.

The presumption of the model calculation was that 9.5% liquid transport fuels would be substituted by biomethane, which depending on the type of fuel would replace 90.6 million liters of diesel, or 104 million liters of petrol fuel consumption per year. The transition to biomethane would reduce these consumption levels, but increase the consumption of fuels required for the biomethane production (spent fuel for the production and logistics of herbaceous biomass): 5.3 to 7.1 million liters per year. It was estimated that petrol and diesel consumption would be replaced by the use of biomethane in the range of 78.5 to 100.6 million Nm^3 per year. Additionally, the modelling assumed 1.5% biomethane losses during production (2.0 to 2.5 million Nm^3 per year).

2.1.2 System boundaries and allocation

In ISO 14044:2006 standard the requirement for defining the product's system and a FU of the LCA is stated. Typically, an LCA covers all environmental impacts from all processes in the entire chain, however in order to compare alternatives, it is not necessary to include identical processes in a consequential LCA to the compared systems (Pehme 2013). Current master's thesis also focused on the differences, and the processes, that were identical for the reference scenarios and the alternative technologies have been omitted.

The investigated system of the current thesis begins with the production of silage and dairy manure, that would be anaerobically digested in 2 different capacity biogas production unit plants. The generated biogas would be used to replace 9.5% of the fossil fuels currently used in the road transport.

The development of infrastructure (buildings, machinery, roads) was excluded from the analysis, as the relative importance to total emissions is presumably low. Various studies (Jury et al. 2010; Poeschl et al. 2010) neglected the GHG emissions related to the construction of an AD plant during the observed full life cycle (expected to be less than 1%).

Additionally, biogenic CO_2 emissions related to the naturally occurring carbon cycle, and CO_2 emitted by the combustion, harvest, digestion, fermentation decomposition or processing of biologically-based materials, were not considered to fit into the scope of this LCA.

Gaseous emissions (e.g. CH_4 through enteric fermentation or CO2 through respiration) from the animals have been excluded from the system boundaries as well, as biogas production (or manure management in general) from animal manure has no effect on the enteric fermentation nor on the respiration.

The Land use, land-use change and forestry (LULUCF) sector's emissions were not considered in the system's boundaries as no land-use category changes were foreseen (according to the Intergovernmental Panel on Climate Change (IPCC) methodology). Although it was presumed that biomass removal from (fallow) agricultural grasslands increases, no additional emissions would occur under the LULUCF sector accounting as no enhanced tillage activity (plowing) would take place as a result of the increased biomass removal. The IPCC methodology also assumes that the soil organic carbon stock under constant land use remains unchanged (IPCC, 2006c).

The biomethane scenarios were compared against the reference scenario, that assumed a business as usual (BAU) situation, where the fossil fuels would be used to the same extent as in recent years, and the manure storaged outside in a liquid manure storage facility or in heaps in case of solid manure prior field application.

Only the emissions generated in the timeframe of one year and on Estonian territory were accounted for in the emission balance.

The mass flows of all the scenarios are visualized on Figure 2.1. The avoided emissions depicted on the figure represent the emission flows of the reference scenario.

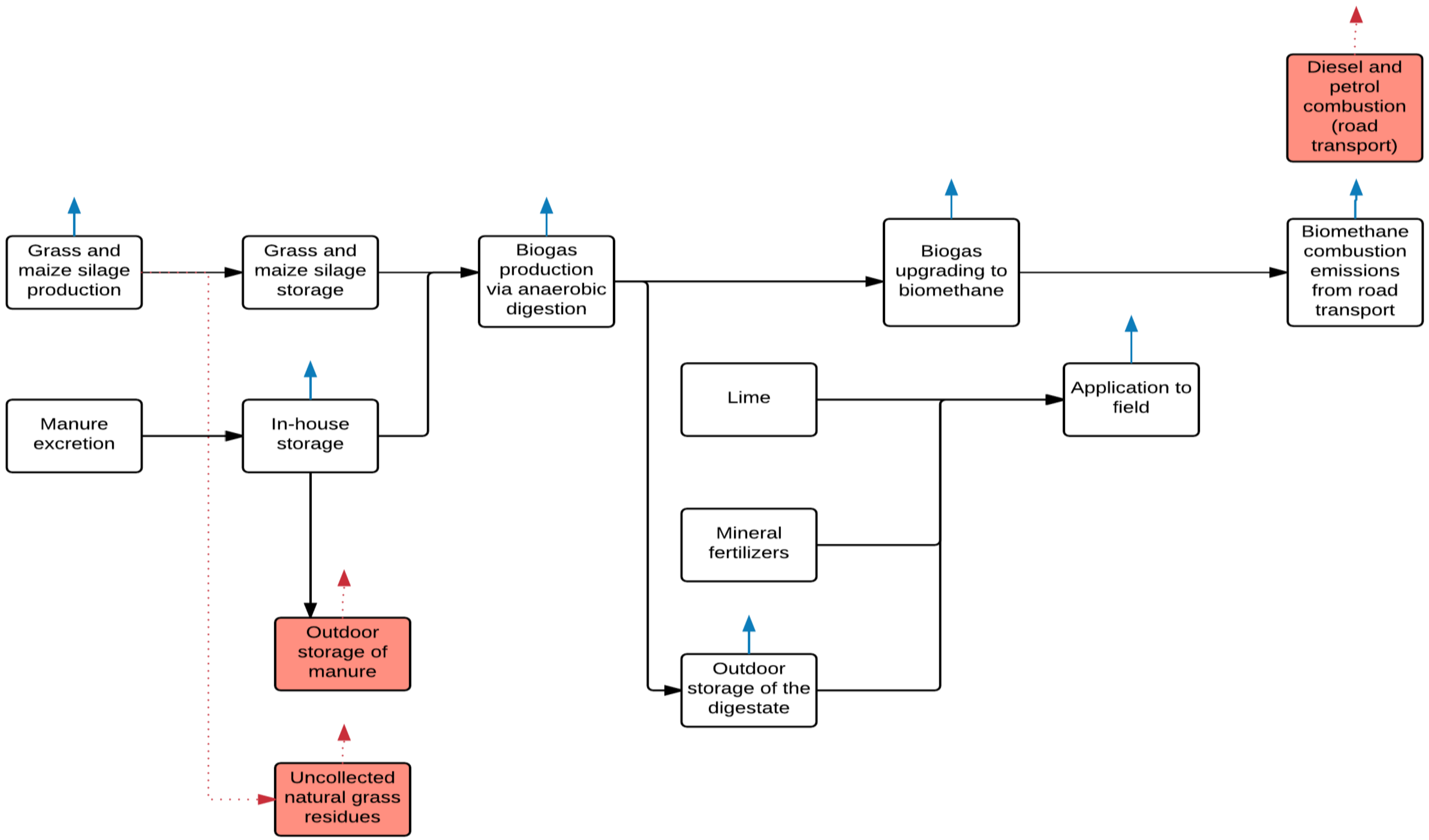

Figure 2.1 Mass flows of the scenarios, where the red dotted arrows indicate the avoided mass flows and emissions from reference scenario, black arrows indicate mass flows and blue arrows emissions taken into account in the biomethane scenarios

2.1.3 Background Research and Data Collection

The GHG emission estimates have been compiled using the methodology and the structure proposed by the IPCC 2006 Guidelines. This makes it coherent with the annually composed national GHG inventories and makes it possible to directly compare the results of this study to the inventory and estimate the impact of the proposed measures to the annual reported GHG emission balance and to the biennial GHG projections submitted to the United Nations Framework Convention on Climate Change (UNFCCC).

Generally, country-specific data about Estonia have been applied in this study, but in case country specific data was unavailable, data about other countries with similar conditions were applied.

Emission factors (EF), data about the mass balances and methodology applied were to a large extent adopted from the thorough works compiled by Pehme (2014) and Hamelin et al. (2014). The named researches rely on the sources described in the subsequent paragraphs.

Data for the reference system, manure composition and EFs for NH_3 were based on Estonian-specific data for liquid manure management in accordance with the recommendations and regulative documents by the Ministry of the Environment and acts of the Riigikogu (Estonian Parliament).

EFs for CH_4 and N_2O were taken from the IPCC 2006 Guidelines for National Greenhouse Gas Inventories from the IPCC. EFs for nitrogen monoxide (NO) and nitrogen are based on *EMEP/EEA air pollutant emission inventory guidebook 2013 - Technical guidance to prepare national emission inventories* from the European Environment Agency. Where necessary, these factors have been combined with other data sources. The biogas production processes have been modelled based on information from the Danish Environmental Protection Agency combined with Danish literature.

Considering the goal of the current master's thesis to analyze the results of the research conducted by Vohu (2015), then most of the metadata have been received from the named study or via personal communication and been implemented without any changes if possible. However, due to different methodologies or the lack of appropriate data, applied model for the life cycle had to be modified to some extent which is elaborated in the relevant chapters.

2.1.4 Impact categories

Environmental effects are the result of a physical interaction between an observed system and the environment. In practical terms all environmental effects can occur in several forms of environmental problems (Zbicinski et al. 2006). The key results of the study were founded on three environmental impact indicators:

- Acidification Potential (AP), m^2 UES[1];
- Aquatic Eutrophication Potential (EP), g NO_3eq; and
- Global Warming Potential (GWP), g CO_2eq.

2.2 Life Cycle Inventory Analysis

The following chapter includes the data collected during the Life Cycle Inventory analysis (LCI) phase for biomethane production and for the reference scenarios. The LCI mainly involves the collection of data on resource use and emissions for the background process steps, together with the actual modelling of the life cycle of the analyzed system. Inspection of preliminary data is carried out in this phase. The Life Cycle Impact Assessment (LCIA) phase interprets the LCI results in the light of the selected impact categories and includes the calculations of the potential environmental impacts in each category such as climate change, acidification, land-use etc. (Wolf et al. 2012).

The calculations performed and the methodology applied were executed in order to quantify and compare the environmental burden against the reference scenario when replacing 9.5% of fossil fuels used in road transport with biomethane. The results of the inventory are presented for all the relevant unit processes affecting biomethane production from silage and manure and for the replacement of fossil fuels and exhibited in units that are easily convertible into FU in order for the calculations of different unit processes to be compatible and comparable to each other.

The advisable tools to perform the LCI calculations are to use a spread sheet system (Talve & Põld 2005). The model of the given LCA was designed and built using Microsoft Excel as the primary user interface, which was chosen because of the universal application of Excel. The

[1] The EDIP2003 AP correlation with its unit of measure per FU are expressed as “the area of ecosystem within the full deposition area which is brought to exceed the critical load of acidification as a consequence of the emission (area of unprotected ecosystem = m^2 UES/FU.)”.

model consists of linked calculation worksheets relevant to each of the major processes involved in biogas production and reference scenarios. The method used to conduct the LCI and the LCIA is in correspondence with the ISO 14044:2006 guidelines.

2.2.1 Reference scenario

The relevant processes of the reference scenario conveying differences in comparison with the biomethane production scenarios are manure management, silage production from semi-natural and cultivated grasslands, and the combustion of fossil fuels. All the emissions calculated under the reference scenario were considered as avoided emissions in the LCIA phase.

Manure management

The main preconditions applicable for the reference slurry system for dairy cows in Estonia as described by Pehme (2013) are an uninsulated loose housing with beds and rubber mats, where slurry is collected to pre-tank where slurry is pumped towards outdoor storage at least once a day. The outdoor storage takes place in a concrete slurry tank covered by a natural crust floating layer.

In order to assess emissions arising from manure management of solid manure, the adjusted data about Poland described in the Baltic manure project have been used. The LCI data of solid manure was compounded presuming the animals are located in loose-housing with deep litter, the manure is removed manually and stored in a field heap where it is evacuated with a tractor equipped with a front loader. The data used in the LCI for 1000kg of manure excreted by dairy cows (ex-animal) and for the manure from animal housing (ex-housing) are given in Table 2.1 and Table 2.2.

Table 2.1 Data used in the LCI for the reference scenario manure management (Hamelin et al. 2013 - Estonian data for slurry and adjusted Polish data for solid manure)

	ex-animal	**ex-housing**
Slurry		
Mass (t/animal y)	22.9	24.9
Total N (kg/ t manure)	5.9	5.1
NH_4-N kg/t manure	3.5	3.0
Solid manure		

	ex-animal	ex-housing
Mass (t/animal y)	21.8[2]	32.5[3]
Total N (kg/ t manure)	8.9	6.0
NH_4-N kg/t manure	5.36	1.2

Table 2.2 EFs used in the LCI for the reference scenario, manure management (Hamelin et al. 2013 - Estonian data for slurry and adjusted Polish data for solid manure), kg/ 1000kg manure

	ex-housing	outdoor storage
Slurry		
Ammonia (NH_3-N), kg	0.4425[4]	0.4200
Direct emissions of nitrous oxide (N_2O-N), kg	0.0090	0.0190
Nitrogen monoxide (representing total NO_x) (NO-N), kg	0.0002	0.0001
NO_3-N, kg	0	0
Nitrogen (N_2-N), kg	0.0110	0.0090
N_2O-N (indirect), volatilization, kg	0.0044	0.0042
N_2O-N (indirect)[5], P, leaching, kg	0	0
CH_4*	0.019	1.171[6]
Solid manure		
NH_3-N, kg	1.34	0.39
N_2O-N, kg	0.0004	0.0440
Nox (NO-N), kg	0.0250[7]	0.0056
NO_3-N, kg	0	0
N_2-N, kg	1.6080	0.3600
N_2O-N (indirect), volatilization, kg	0.0031	0.0120
N_2O-N (indirect) [3], P leaching, kg	0	0
CH_4*	0.025	0.225[8]

*CH_4 emissions are based on the methodology described in the IPCC guidelines:

CH_4 [kg] = VS [kg] × B_0 × 0.67 [kg CH_4 per m^3 CH_4] × MCF

Where:

VS : The amount of volatile solids as excreted by the animals (kg)

B_0 : The maximum CH_4 producing capacity for a given manure (m^3 CH_4 kg^{-1} VS excreted) (CH_4 potential)

MCF : CH_4 conversion factor (%)

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[2] Value ex-animal based on (Kaasik 2013)

[3] Based on mass balance. Additionally, 2.35t per animal year water loss (evaporation) was accounted in according to data presented in Hamelin et al 2013 in the named research table 2.1 and 2.4

[4] 7.5% of N from housing is lost as NH_3 (Regulation of the Minister of the Envrionement No. 48 2008)

[5] No leaching from leak-tight storage facilities is assumed (Kaasik et al. 2013)

[6] MCF =10%. This gives the total emission for in-house and outdoor storage, from which the emission from in-house storage was deducted. Bo=0.24 (IPCC 2006a); VS (calculated based on average 2014 Estonian data and IPCC methodology, for calculation details see NIR 2016)

[7] NOx-N=0.01 kg NO per kg TAN ex-animal *14/30 (EMEP & EEA 2013b)

[8] MCF =2%. This gives the total emission for in-house and outdoor storage, from which the emission from in-house storage was deducted. VS(calculated based on average 2014 Estonian data and IPCC methodology, for calculation details see NIR 2016)

The changes taking place in the manure composition during each step of manure management are important to consider in the LCI as it directly influences the emissions arising from each step of manure management starting from the moment manure leaves the cow (ex-animal) to the moment the manure is spread on the field for fertilization. The changes in dairy slurry and solid manure composition are presented in Table 2.3 (Hamelin et al. 2013).

Table 2.3 Changes in dairy slurry and solid manure composition, kg/ 1000 kg manure (Hamelin et al. 2013)

	ex-animal	**ex-housing**
DM manure per 1t manure		
Slurry	114.9	114.8
Solid	113.5	311.4
VS manure per 1t manure		
Slurry	92.6	94.3
Solid	90.8	290.8
N		
Slurry	5.9	5.1
Solid	8.9	6.0
P		
Slurry	1.3	1.2
Solid	0.9	0.8
K		
Slurry	4.4	4.1
Solid	4.9	7.1
C		
Slurry	59.6	54.8
Solid	51.7	126.2
Mass		
Slurry	22.9	24.9
Solid	21.8	30.5

Silage production

Considering the evaluation of Estonian grasslands' yield (2.2 million tons of DM/year) presented in the study by Vohu (2015) current master's thesis was grounded on, an estimated 64% of herbal biomass (1.4 million tons of DM/year) is in practice not used as animal feed, instead the biomass is mowed, crushed and left on the fields to decay. Partially the crushed biomass is piled up on the sides of the fields and left there to decompose, and is marginally used as a bedding material for animals (Kaasik & Vohu 2014)

The land use in the reference scenario was designed with the presumptions that in the 5M unit scenarios 15% of natural grass (NG), 25% of maize silage and 65% of grass-clover silage are used as the biogas substrates. The division in the land-use portfolio for the 2M unit scenarios was presumed to be 15% of NG and 85% of grass-clover mixture. The background emissions from the reference scenario were estimated based on the same land use portfolio (Vohu 2015).

The decomposition of the grass and crop residues generates nitrate in the weeks and months after termination and hence increase the risk of N_2O emissions (Cornell University 2016). As a result, levels of N_2O emissions are higher from managed agricultural land, where the hay is harvested, but left on the field to decay. This in turn magnifies the quantities of crop residues left behind on the field, compared to conditions where the crops are harvested and gathered from the field as presumed in the biomethane scenarios.

The IPCC 2006 Guidelines Tier 1 methodology (IPCC 2006b) was implemented in order to calculate direct (Equation 2.1) and indirect N_2O emissions from the degradation of grass and maize silage residues. The EF was assumed equal to 0.1 kg N_2O-N of kg N applied. In order to estimate the N_2O emissions from crop residues left on the field, it was necessary to determine the amount of above and below ground residues and their nitrogen content. For this, the methodology and default parameters (detailed below) from IPCC 2006 guidelines were applied

$$F_{CR} = \sum_T \left\{ Crop_T \times \left(Area_T - Area\ burnt_{(T)} \times C_f \right) \times Frac_{Renew(T)} \times \left[R_{AG(T)} \times N_{AG(T)} \times \left(1 - Frac_{Remove(T)}\right) + R_{BG(T)} \times N_{BG(T)} \right] \right\} \qquad \text{Equation 2.1}$$

Where,

F_{CR}=the amount of N in crop residues (above-ground and below- ground), including N-fixing crops, returned to soils annually;

R_{AG} = ratio of above-ground residues dry matter to dry matter yield (0.3 for each crop);

N_{AG} = N content of above-ground residues dry matter (maize: 0.006 kg /kg N, grass-clover mixture: 0.025 kg /kgN , natural grass: 0.015 kg/ kg N);

R_{BG} = ratio of below-ground residues dry matter to dry matter yield (maize: 0.29, grass-clover mixture and natural grass 1.04);

N_{BG} = N content of below-ground residues dry matter (maize:0.007 kg/ kgN, grass-clover mixture: 0.016 kg /kg N , natural grass: 0.012 kg /kg N).

Indirect N_2O emissions were also considered. Among the indirect N_2O emissions IPCC Guidelines instruct the calculation of N_2O due to leaching and runoff (EF: 0.0075 kg N_2O-N kg of kg N leached and runoff) and N_2O due to NH_3 and NO_x volatilization (EF: 0.1 N_2O-N kg of kg NH_3 and NO_x volatilized). The following parameters were used:

$Frac_{GASF}$ = synthetic N fertilizer fraction that volatilizes as NH_3 and NO_x – (default 0.1 kg of kgN applied);
$Frac_{GASM}$ = organic N fertilizer fraction that volatilizes as NH_3 and NOx – (default 0.2 kg of kg N applied or deposited);
$Frac_{LEACH}$ = N applied fraction lost through leaching and runoff – (default 0.3 kg of kg N applied).

Transport emissions

In the premises about the transport fuel market economic analysis applied in the current master's thesis, the data of 2013 on petrol and diesel fuel consumption in Estonia were used, according to which 829 000 tons of diesel and petrol were used as transport fuels (Vohu 2015). As the current master's thesis considered 9.5% of liquid road transport fuels to be replaced by biomethane, then it was also considered to be the amount of fossil fuels used in the reference scenario. The emissions arising from using the aforementioned volumes of diesel and petrol fuels were considered in the reference scenario emission flow. The main assumptions about the transport fuel market affecting this study are presented in Table 2.4.

Table 2.4 Assumptions about the transport fuel market (Vohu 2015)

	Diesel	**Petrol**	**Total**
Fuel consumption (1000t in 2013)	595.0	234.0	829.0
Volume weight (kg/m^3)	885.0	737.2	
Amount as the volume unit	672.3	317.4	989.7
Calorific value (MJ/l)	38.6	34.2	
Energy consumption (TWh)	7.2	3.0	10.2
Replacement with electric transport (0.5% replacement; TWh)		0.1	0.1
Energy consumption after electric transport (TWh)	7.2	3.0	10.2
Energy replaced with biomethane (TWh)	0.6883*	0.2830*	0.9713

*The values for energy replaced with biomethane are valid for the proportional substitutions and may differ depending on the scenario

The aim to replace liquid fuels equaling 1 TWh per year was dependent on the fuel type replaced, whereas the amount of biomethane needed for substituting the acquired amount, might differ (Vohu 2015). The table below shows the volumes of biomethane being replaced according to the type of fuel substituted in the different scenarios and the Table 2.5 includes the

EFs used in the LCI to model the environmental impacts from the combustion of diesel and petrol fuels.

Table 2.5 Substitution of biomethane (Vohu 2015)

	Diesel	**Petrol**	**Total**
Replaced energy (TWh):	0.9713		
Co-efficient for CH_4 fuel replacement:	1.41	1.1	
Heating value of biomethane(kWh/Nm^3):	9.8	9.8	
Replaced volumes of biomethane dependent on the scenario (Nm^3):			
Proportional substitution	99 026 644	31 767 545	**130 794 189**
Petrol substitution	0	109 022 374	**109 022 374**
Diesel substitution	139 746 861	0	**139 746 861**

The EFs used for calculating road transport emissions (Table 2.6) originate from the Estonian Informative Inventory Report (IIR 2015) and from the National Greenhouse Gas Inventory Report (NIR 2016) and represent the average EFs used for calculating road transport emissions for 2013 and 2014. Emission calculations from road transport in IIR (2015) were based on the Tier 3 method[9], whereby exhaust emissions are calculated using a combination of reliable technical and detailed activity data in COPERT 4 programme (Computer Programme to calculate Emissions from Road Transport, Copert 4 version 9.1). Using a combination of default COPERT EFs and activity data (e.g. number of vehicles, annual mileage per vehicle, average trip, speed, fuel consumption, monthly temperatures, driving and evaporation share), total emissions are compounded. The Estonian specific activity data about the vehicle classes are defined by the vehicle category, fuel type, weight class, environmental class, and in some instances, the engine type and/or the emission reduction technology. Calculations also use annual mileage per vehicle category and the number of vehicles, sourced by the Estonian Road Administration (IIR 2015).

Table 2.6 EFs used for calculating avoided emissions from petrol and diesel use (IPCC 2006c; IIR 2015)

	Diesel	**Petrol**	**Comments**
N_2O (kg/TJ)	2.29	1.82	NIR 2016 (average values for Estonian road transport in 2014)
CH_4 (kg/TJ)	2.02	12.16	
CO_2 (t/TJ)	73.13	72.58	
NO_x (kg/l fuel)	0.01	0.004	IIR 2015
SO_2 (kg/ l fuel)	1.09 E-05	8.86 E-06	

[9] Most detailed method with prevailingly country-specific input data and EFs applied as opposed to Tier 1 method, that uses mainly default values.

2.2.2 Biomethane production scenarios

The unit processes associated with biomethane production cover the entire production chain, i.e. substrate production, harvesting and transportation, animal housing, anaerobic digestion of the substrates, fermenting residue management, upgrading of biogas to natural gas quality, provision of energy for the biogas plant and combustion of biomethane in natural gas vehicles.

Production and storage of grass and maize silage

The residual grass from semi-natural grasslands, is reckoned to be currently underused and posing a considerable biogas potential by several authors (Heinsoo et al. 2010; Pehme et al. 2014).

The analyses regarding the exploited resources of grasslands have indicated that approximately 300-350 thousand ha (about one-third of arable land in Estonia) are underused and the farmers mainly rely on agricultural subsidies as a source of revenue. It poses difficulties to find suitable use for this biomass. Some areas are used for animal grazing but the minimum management is mowing the hay once a year. Although, due to technical nuances it is preferable to use simultaneously other substrates (such as slurry or maize silage) in the biogas production process as well (Kaasik & Vohu 2014).

The land use of this LCA was designed based on the assumptions that in the 5M unit scenarios 15% of natural grass (NG), 25% of maize silage and 65% of grass-clover silage are used as the biogas substrates as already mentioned in the reference scenario. The division in the land-use portfolio in 2M unit scenarios was presumed to be 15% of NG and 85% of grass-clover mixture. In addition, it was assumed that the production of the needed silage uses the existing cropland and no land use change will occur. Consequently, there will be no change in emissions under the LULUCF sector compared to the reference scenario.

The production of herbaceous biomass as a biomethane production substrate (silage production), depending on the scenario would cover 64.8 to 93.3 thousand hectares of agricultural land, out of which approximately 15% are semi-natural permanent grasslands and about 25% of the grassland crops are annually renewed. The total quantities and crop yields of silage used in the biogas production process in different scenarios are shown in Table 2.7 and Table 2.8.

Table 2.7 Amounts of silage used in different scenarios for generating biogas (Vohu 2015)

Scenario[10]	**Pr5M**	**Pr2M**	**P5M**	**P2M**	**D5M**	**D2M**
Herbaceous biomass/production unit	35 000	19 800	35 000	19 800	35 000	19 800
Maize silo/production unit	20 000	0	20 000	0	20 000	0
No.of biogas plants	26	64	22	54	28	69
Maize silo, t/TWh	520 000	0	440 000	0	560 000	0
Herbaceous biomass, t/TWh	910 000	1 267 200	770 000	1 069 200	980 000	1 366 200
...Grass-clover mixture	761 370	1 060 228	644 236	894 568	819 937	1 143 059
...Perennial grasses from natural grasslands	148 630	206 972	125 764	174 632	160 063	223 141

Table 2.8 Crop yield used in the calculations (Vohu 2015)

Scenario[10]	**Pr5M**	**Pr2M**	**P5M**	**P2M**	**D5M**	**D2M**
Crop yield, kg fresh weight/ha	Maize		Grass-clover mixture		Perennial grasses	
	25 000		19 200		12 000	

The storage processes will result in change in mass balance of mass and grass silage which was important to take into account when modelling the subsequent processes and the final yield of biogas. The changes in mass balance compared to the delivered silage composition are presented in Table 2.9 for maize silage and in Table 2.10 for the grass-clover mixture and perennial grasses from natural grasslands.

Table 2.9 Change in mass balance of maize silage during storage (Hamelin et al. 2014a)

	Maize silage "as delivered"	**Mass balance: Change during storage**	**Mass balance: Amount after storage**	**Maize silage "ex-storage"** [b]
	kg/1 000.0 kg maize silage "as delivered"	kg	kg	kg/1 000.0 kg maize silage "ex-storage"
Total mass	1 000.0	- 8.0	992.0	1 000.0
DM	310	- 6.0	304.0	306.5
VS	294.5	- 6.0 [a]	288.5	290.8

[10]D2M Diesel replacement and 2 million Nm3 yearly output capacity biogas production plants
D5M Diesel replacement and 5 million Nm3 yearly output capacity biogas production plants
P2M Petrol replacement and 2 million Nm3 yearly output capacity biogas production plants
P5M Petrol replacement and 5 million Nm3 yearly output capacity biogas production plants
Pr2M Proportional replacement of diesel and petrol fuels according to the proportion of contemporary consumption and 2 million Nm3 yearly output capacity biogas production plants
Pr5M Proportional replacement of diesel and petrol fuels according to the proportion of contemporary consumption and 2 million Nm3 yearly output capacity biogas production plants

	Maize silage "as delivered"	Mass balance: Change during storage	Mass balance: Amount after storage	Maize silage "ex-storage" [b]
	kg/1 000.0 kg maize silage "as delivered"	kg	kg	kg/1 000.0 kg maize silage "ex-storage"
Total N	4.31	No change	4.31	4.34
Phosphorus (P)	0.81	No change	0.81	0.81
Potassium (K)	3.72	No change	3.72	3.75
Carbon (C)	139.5	- 1.36	138.1	139.3

[a] Assumed to be the same change as for DM;
[b] Same data as in the "amount after storage" column, but adjusted to be expressed per 1 000.0 kg of maize silage "ex- storage".

Table 2.10 Change in mass balance of natural grass silage during storage (Pehme 2013)

	NG as delivered	Change during storage	Amount after storage	NG after storage
Unit	**Kg/1000kg as delivered**	**kg**	**kg**	**Kg/1000 kg after storage**
Total mass	1000	-27.9	972.1	1000
DM	310	-27.9	282.1	290.2
VS	297.6	-27.9	269.7	277.4
Total N	4.65	No change	4.65	4.78
Phosphorus (P)	1.86	No change	1.86	1.91
Potassium (K)	4.65	No change	4.65	4.78
Carbon (C)	145.7	-1.83	145.7	149.9

The N_2O emissions arising from crop residues left on the field after harvesting are compounded with the methodology described in Chapter 2.2.1 under section silage production.

Manure management

The LCI data about manure management are reported for 2M and 5M capacity biogas production units. The amounts of manure used for generating biogas in different scenarios are given in Table 2.11 manure management emissions taken into account in all the biogas production scenarios are the barn emissions resulted from housing of dairy cattle. The emissions from the barn storage of manure equal to the barn storage emissions of the reference manure in the reference system. The composition of the dairy cow slurry and solid manure exiting the animal housing unit is equal to the composition of the reference dairy manure described in chapter 2.1.2 (manure ex-housing).

Table 2.11 Amounts of manure used in different scenarios for generating biogas (Vohu 2015)

Scenario[10]	**Pr5M**	**Pr2M**	**P5M**	**P2M**	**D5M**	**D2M**
Slurry, t/production unit	12 500	25 000	12 500	25 000	12 500	25 000
Solid manure, t/production unit	4 000	8 000	4 000	8 000	4 000	8 000
No.of biogas plants	26	64	22	54	28	69
Cattle slurry, t/TWh	325 000	1 600 000	275 000	1 350 000	350 000	1 725 000
Cattle solid manure, t/TWh	104 000	512 000	88 000	432 000	112 000	552 000

Biogas Production

The energy input of biomethane production was calculated to be 105.3 to 135.7 GWh of electricity, and 185.3 to 241.2 GWh of heat[11]. Electricity would be bought from transmission network and the purchase and production of heat is expected to be provided by on-site woodchip boiler operation - the task could also be executed by the use of combined heat and power.

Biogas production examined in the current master's thesis was considered to be a two-step anaerobic digestion at mesophilic temperatures (ca 37 °C. the density of biogas is 1.158 kg/Nm3.(Hamelin et al. 2014b). The CH_4 yield and CH_4 content used in the calculations is presented in Table 2.12.

Table 2.12 CH_4 yield and CH_4 content used in the calculations (Pitk 2015)

Substrate	**Methane yield, Nm³/Vs**	**CH_4 content of biogas**
Maize silage	433.3	52%
Natural grass silage	370.7	52%
Solid manure	166.7	56.5%
Slurry	94.8	56.5%

The biomass entering the digester was considered to be a mixture of dairy cow manure "ex-housing" and natural grass and maize silage "ex-storage". The fraction of the substrates used in the mix entering the digester in different scenarios were based on activity data based originate from the work of Vohu (2015) **(**Table 2.7 and Table 2.11). Calculation procedure was carried out supported by the methodology described in Hamelin et al. (2014b), composition of both materials (Table 2.3, Table 2.9, Table 2.10 and Table 2.13) and CH_4 yields and CH_4 content of the biogas in Table 2.12.

[11] Same data applied as in Vohu (2015 carried out by Peep Pitk, researcher of Department of Chemistry in Tallinn University of Technology. Data were provided through personal interview with Villem Vohu.

Biomass mixture was calculated to consist of 13% VS manure (ex-housing) and of 87% VS natural grass along with maize silage for 5 Nm3 biogas production units and 47% VS manure (ex-housing) and 53% VS natural grass as a percentage for 2 Nm3 biogas production units.

To demonstrate, the amount of biogas produced in a 5Nm^3 unit from 1 ton of mixture is 132.8 Nm^3 and was calculated as follows:

- Biogas from manure: (186.05 kg slurry ex-housing * 94.3 kg VS/1000 kg manure ex- housing* 94.8 Nm3 CH4/t VS + 76.56 kg solid manure ex-housing * 290.8 kg VS/1000 kg manure ex-housing*166.69Nm3 CH4/t VS)/ 0.65 * t/1000 kg = 8.26 Nm^3 biogas.

- Biogas from natural grass: 465.78 kg natural grass silage ex-storage * 277.4 kg VS/1000 kg natural grass ex-storage * 370.73 Nm3 CH4/t VS / 0.65 * t/1000 kg = 73.69 Nm^3 biogas.

-Biogas from maize silage: 271.6 kg maize silage ex-storage * 290.8 kg VS/1000 kg maize silage ex-storage * 433.3 Nm^3 CH4/t VS / 0.65 * t/1000 kg = 52.65 Nm^3 biogas

The composition of biomass entering the digester is presented in the table below. For the 5 Nm^3 biogas production units there is 26.261% of manure in the mixture and 73.739% of silage (wet weight) and for the 2M units the mixture entering the digester constitutes of 66.592% of manure and 33.408% of herbaceous biomass (wet weight) (Table 2.13).

Table 2.13 Composition of biomass mixture entering to the digester (presented separately for 5M Nm^3 and 2M Nm^3 unit biogas production plants)

	Solid manure and slurry after storage[12]	**Silage after storage**[13]	**Mass balance to manure**	**Mass balance to silage**	**Mixture entering to the biogas reactor**
5M	kg/1000kg manure	kg/1000 kg silage	kg/ 262.61 kg manure ex-housing	kg/737.39 kg silage	kg/1000kg biomass mixture
DM	139.75	296.20	36.70	218.42	255.12
VS	122.09	282.34	32.06	208.19	240.25
N	4.55	4.62	1.20	3.41	4.60
P	0.96	1.50	0.25	1.11	1.36
K	3.10	4.40	0.81	3.24	4.06

[12] Solid manure and slurry entering to the digester in proportions presented in

Table 2.**11**

[13] Natural grass and maize silage according to the proportions presented in Table 2.7

	Solid manure and slurry after storage[12]	**Silage after storage[13]**	**Mass balance to manure**	**Mass balance to silage**	**Mixture entering to the biogas reactor**
C	62.02	146.00	16.29	107.66	123.94
2M	kg/1000kg manure	kg/1000kg silage	kg/665.92kg manure ex-housing	kg/ 334.08kg manure ex-housing	kg/1000kg biomass mixture
DM	139.75	290.20	93.06	96.95	190.02
VS	122.09	277.40	81.30	92.67	173.97
N	4.55	4.78	3.03	1.60	4.63
P	0.96	1.91	0.64	0.64	1.28
K	3.10	4.78	2.06	1.60	3.66
C	62.02	149.90	41.30	50.08	91.38

The data about the changes occurring in mass balances of the biomass before and after the anaerobic digestion presented in Table 2.14 were relevant for the nutrient balance on the basis which the need for inorganic fertilizers was later compounded. The data used for calculating the emissions arising from the biogas production process are shown in Table 2.15 and the EFs applied estimating the air emissions originating from the electricity and heat energy production used by the biomethane production plant are aggregated in Table 2.16.

Table 2.14 Mass balances for the biomass before and after the anaerobic digestion for 5Nm3 and 2Nm3 production units (methodology applied described further in Hamelin (2014))

	Biomass mixture entering the digester[a], kg/1000 kg biomass mixture	**Mass balance: change during biogas digestion, kg**	**Mass balance: amount after biogas digestion, kg**	**Digestate "ex-digester" kg/1000kg digestate**
5M				
Total mass	1000.00	153.76[b]	846.24	1000.00
DM	255.12	153.76[c]	101.36	119.77
VS	240.25	153.76[d]	86.49	102.21
N	4.60	no change	4.60	5.44
P	1.36	no change	1.36	1.61
K	4.06	no change	4.06	4.80
C	123.94	71.4[e]	52.53	62.07
2M				
Total mass	1000.00	80.11	919.89	1000.00
DM	190.02	80.11	109.90	119.48
VS	173.97	80.11	93.86	102.04
N	4.63	no change	4.63	5.03

	Biomass mixture entering the digester[a], kg/1000 kg biomass mixture	Mass balance: change during biogas digestion, kg	Mass balance: amount after biogas digestion, kg	Digestate "ex-digester" kg/1000kg digestate
5M				
P	1.28	no change	1.28	1.39
K	3.66	no change	3.66	3.98
C	91.38	37.21	54.18	58.89

[a]All the same data as the composition of biomass mixture in Table 2.13 in the column "biomass mixture entering digester"
[b] The loss corresponds to the mass of biogas produced in Table 2.15
[c] Change in dry matter equals to change in total mass.
[d] The same change as for DM (all DM loss was VS).
[e] C loss corresponds to the losses in the biogas itself (e.g. 5M: the sum of CH_4 -C and CO_2 -C: (134.5 Nm^3 *52.2% * 0.717 kg CH_4 /Nm^3 CH_4) * (12.011 g/mol/16.04 g/mol) + (134.5 Nm^3 biogas * 47.8% CO_2* 1.977 kg CO_2/Nm^3 CO_2) *(12,011 g/mol/44,01 g/mol) = 71.4 kg C, where 0.717 kg CH4/Nm^3 CH_4 is methane density and 1.977 kg CO_2/Nm^3 CO_2 is the carbon dioxide density.

Table 2.15 Data for the LCI: biogas production for 5Nm^3 and 2Nm^3 production units (adapted methodology from Hamelin (2014))

Production Unit	**5M**	**2M**	**Comments**
Input	**value**	**value**	
Electricity, MWh/yr	1833	750	Presumably produced from oil shale (Pitk 2015)[11]
Heat, MWh/ yr	8551	3500	Heat produced from wood chips and CNG
Electricity, kWh/yr (for 1000kg biomass)	25.09	13.02	Pitk 2015[11]
Heat, kWh/ yr (for 1000kg biomass)	421.43	218.70	
Biomass mixture, kg	1000	1000	Amount of biomass mixture entering to the anaerobic digester (corresponding compositions described in (Table 2.13). Table 2.**13**)
Output (emissions from electrical and heat energy consumption, results presented for biomass mix of 1000kg)			
CO_2, kg	1.8356	0.9507	CO_2oilshale = EF * TJ of electricity /1000*0.98*44/12 (average EF 27.65 t C/TJ); CO_2 CNG = biogenic emissions- not estimated (NIR 2016) (Table 2.16)
CH_4, kg	0.0036	0.0019	NIR 2016 (Table 2.16)
N_2O, kg	0.0004	0.0002	
NO_x, kg	0.2721	0.1402	IIR 2015 (Table 2.16)
SO_2, kg	0.0117	0.0060	

Production Unit Input	5M value	2M value	Comments
Output (results presented for biomass mix of 1000kg)			
Biogas (on average 5M: 52.2% CH_4 and 47.8% CO_2; 2M: 53.1% CH_4 and 46.9% CO_2), kg	153.8	80.1	5M unit: 132.8 Nm^3 biogas *1,158 kg biogas/Nm^3 biogas (biogas density) = 153.8 kg biogas. No water loss. The only loss is the mass of biogas: 1000 kg biomass – 153.8 kg biogas = 846.2 kg digestate.
Digestate, kg	846.2	919.9	
Air emissions	All CH_4 losses would presumably take place at the refining stage.		
Discharge to water and soil	No emissions are assumed to occur		

Table 2.16 EFs used for emission estimates from heat and electricity production, kg/ TJ (IPCC 2006d; NIR 2016)

Gas	Biomass	CNG	Oil Shale$_{\text{Pulverized combustion}}$	Oil Shale$_{\text{Circulated fluidized bed combustion}}$
CO_2-C			27 850	26 940
CH_4	30	1	0	0
N_2O	4	0.1	0	0.8
NO_x	100	100	118	71
SO_2	10	0.28	735	0

Biogas upgrading to biomethane

The CO_2, H_2S and water vapor in biogas have practically no use as fuel. CH_4 is the easily combustible content in biogas whereas CO_2 being a noncombustible limits its compressibility and is difficult to be stored in cylinders (Shah & J., Nagarsheth 2015). The purpose of cleaning the biogas is to increase the share of CH_4 in the biogas from the usual 50-75% to more than 95% by removing CO_2, H_2S and water vapor to make it suitable as engine fuel (SEAI 2012). The purified biogas is usually referred to as biomethane. According to Estonian standard in order for the biomethane to qualify for natural gas grid injection, the content of CH_4 in biogas

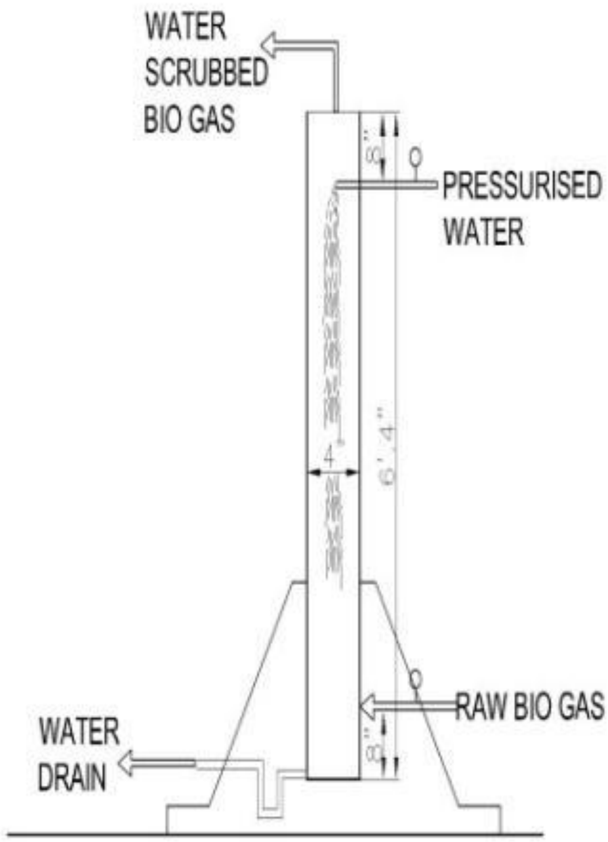

Figure 2.2 Operating principle of a Water Scrubber (reproduced from Shah & J., Nagarsheth, 2015)

has to reach at least 98% (±1%) (Eesti Gaas 2016). CH_4 losses in the process of upgrading were considered to be 1.5% and the hypothetical technology used for upgrading was recommended by Ülo Kask in an interview and considered to be water scrubbing, which is believed to suit Estonian conditions.

Water scrubbing features physical absorption of CO_2 and H_2S in water at high pressure and subsequent regeneration by a release in pressure with a slight change in temperature (Figure 2.2). Carbonic acid is formed in a chemical reaction between CO_2 in biogas and water(Shah & J., Nagarsheth 2015): $CO_2 + H_2O \rightarrow H_2CO_3$.

Water scrubbing is the most inexpensive and simplest method used for biogas upgrading, where pressurized water is used as absorbent. The raw biogas can be passed at storage pressure or compressed and directed to scrubber column from bottom, while from top of the column pressurized water is sprayed though nozzles. Both CO_2 and H_2S are more soluble than CH**4** in water which makes selective removal of the former gases through physical absorption possible. As the content of H_2S in biogas is less than 1% (Shah & J., Nagarsheth 2015), the H_2S emissions from the removal were not considered in this step of the LCA. The data used in the emission estimates of biogas upgrading are presented in Table 2.17.

Table 2.17 LCI data about the biogas upgrading process of 1000Nm^3 of biogas for 5Nm^3 and 2Nm^3 production units

Production Unit	**5M**	**2M**	**Comments**
Input	value	value	
Biogas, Nm^3	1000	1000	
CH_4, Nm^3	531	522	On average the content of CH_4 in biogas for 5M units: 52.2% and for 2M units: 53.1%

Production Unit	5M	2M	Comments
Input	value	value	
CO_2, Nm^3	469	478	On average the content of CO_2 in the biogas for 5M units: 47.8% and for 2M: 46.9%
Electricity: Refining and compressing, kWh	259.99	259.97	Pitk 2015
Output			
Purified biogas, Nm^3	553.125	543.75	≥98% (±1%) of CH_4
CH_4, Nm^3	528.35	519.39	Initial amount of CH_4 – the amount of CH_4 in tail gas
CO_2, Nm^3	22.13	21.75	CO_2 2%
Tail gas	885.374	903.871	Sum of CO_2 and CH_4
CO_2, kg	884	902	CO_2 density 1.977kg/nm3
CH_4, kg	1.904	1.871	1.5% initial CH_4 content makes it to the tail gas (CH_4 density 0.717 kg/Nm^3)

Use of biomethane as a transport fuel and avoided emissions from substitution of fossil transport fuels

Biogenic CO_2 emissions are released from the combustion of biofuels. According to the IPCC 2006 Guidelines carbon in the fuel derived from biomass should be reported as an information item and not included in the sectoral or national totals. The CO_2 emissions emitted by the combustion of biogenic carbon are not considered to contribute to climate change as the carbon in the fuel is absorbed during the growth of the original biological material. Even though CO_2 emissions from biogenic carbon are not accounted for in national totals, the combustion of biofuels as vehicle fuel generates anthropogenic CH_4 and N_2O emissions that should be considered in GHG emission estimates (IPCC 2006c). It was assumed that the upgraded biogas would be used by passenger cars that require on average 0.63 kWh biogas /km and have an annual mileage of 15 000 km per car (Kask et al. 2012). The EFs used for the calculations and their references are presented in Table 2.18.

Table 2.18 EFs used in emission estimates from using biomethane as a transport fuel

CO_2, kg/TJ	0	IPCC 2006c
CH_4, kg/TJ	92	
N_2O, kg/TJ	3	
NO_x, g/km	0.02	Kask et al. 2012
SO_2, g/km	0.00009	

Storage of the digestate

The digestate that is the leftover product of the anaerobic digestion of silage and manure would be utilized for fertilization purposes on maize in early growth stages and on renewed grasslands before plowing and consequently needs to be stored outside for the in-between time period. The calculations were compiled considering the same conditions apply for the digestate storage as for the outside storage of slurry described in Chapter 2.2.1

In compliance with the IPCC 2006 guidelines the main factors affecting CH_4 emissions are the amount of manure produced and the portion of the manure that decomposes anaerobically. The latter is dependent on how the manure (digestate) is managed. When manure is stored as a liquid, it decomposes anaerobically and produces a significant quantity of CH_4 (Methane Conversion Factor (MCF) 10%), considerably less CH_4 is produced when manure is handled as a solid (e.g. in heaps) (MCF 2%) or deposited on pasture (MCF 1%). The CH_4 production is also highly affected by temperature and the retention time of the storage facility (IPCC 2006a).

Table 2.19 contains the data used in order to evaluate emissions occurring from the outdoor storage of the digestate and the next Table 2.20 contains the information about the composition of the digestate before and after the storage.

Table 2.19 LCI data from outdoor storage of the digestate for 5Nm3 and 2Nm3 production units (methodology adapted from Hamelin 2014)

Production Unit	**5M**	**2M**	**Comments**
Input	**value**	**value**	
Digestate, kg	1000		Emissions are calculated for 1000kg after leaving the digester
Water, kg	111		A net water addition of 0.11 m^3 per ton digestate was considered during outdoor storage same as for manure (Hamelin et al. 2014a)
Straw cover, kg	2.5		The production of straw was not accounted as it is considered a waste (Pehme 2013)
Output			
Digestate, kg	1107.9	1108.5	Digestate after storage minus losses (emissions)

Production Unit	5M	2M	Comments
Input	value	value	
Methane (CH_4)	1.54	1.41	Calculated according to IPCC guidelines, using MCF = 10% and B_0 = 0.30 kg CH_4/kg VS for mixture (based on mass balances in mixture, 0.24 kg CH_4/kg VS for manure (IPCC 2006) and 0.31 kg CH_4/kg VS for NG and maize silage). Emission reduction potential factor of 50% was applied for digestate (Nielsen et al. 2009) 5M unit calculation example: 102.207 kg VS/ t digestate * B_0 0.30 kg CH_4/kg VS * 10% IPCC factor * (100-50)% = 1.54 kg CH_4.
NH_3-N, kg	0.45	0.41	EF the same as for slurry storage: 10% of N is emitted as NH_3: 5.44 kg N*10%*(14,007/17,0308) = 0.45 kg NH_3-N (5M unit example) (Regulation of the Minister of the Envrionement No. 48 2008)
N_2O-N (direct emissions), kg	0.03	0.03	0.005 kg N_2O-N per kg N (IPCC, 2006a) as for slurry outdoor storage 0.005 kg*5.44 kgN (5M unit example)
N_2O-N (indirect emissions), kg	0.0045	0.0041	1% of N loss as kg N_2O-N per kg (NH_3-N + NO_x-N) volatilized (IPCC, 2006b). 1%* (0.45+0.00018) kg (5M unit example)
NO-N (representing total NO_x), kg	0.00018	0.00016	NO = 0.0001 of TAN; 70% of total N is TAN: 5.44 kg N/1000 kg digestate * 0.0001 kg NO-N/kg TAN * 70% * (14/30) = 0.00018 kg NO-N. (Pehme 2013)
Nitrogen dioxide (NO_2-N), kg	-	-	No data
Nitrogen (N_2-N), kg	0.01	0.01	N_2-N = 0.003 of TAN; 70% of total N is TAN: 5.44 kg N/1000 kg digestate * 0.003 kg N2-N/kg TAN * 70% = 0.01 kg N_2-N. (Pehme 2013)
CO_2, kg	3.61	3.16	Calculated as a function of the CH_4 emissions, assuming a ratio of 2.351 kg and 2.230 kg CO_2 per kg CH_4 for the mixture for 5M and 2M units accordingly (Pehme 2013)

Table 2.20 Mass balance of the biomass substrate during the storage for 5Nm^3 and 2Nm^3 production units (methodology adapted from Hamelin (2014))

	Biomass mixture entering the digester, kg/1000 kg biomass mixture[a]	Mass balance: change during digestate storage, kg	Mass balance: change after digestate storage, kg	Digestate after storage kg/1000 kg[g]
5M				
Total mass	1000.00	110.88[b]	1110.88	1000.00
DM	119.77	-2.62[c]	117.15	105.46

	Biomass mixture entering the digester, kg/1000 kg biomass mixture[a]	Mass balance: change during digestate storage, kg	Mass balance: change after digestate storage, kg	Digestate after storage kg/1000 kg[g]
VS	102.21	-2.62[d]	99.58	89.64
N	5.44	-0.49[e]	4.95	4.45
P	1.61	no change	1.61	1.45
K	4.80	no change	4.80	4.32
C	62.07	-2.14[f]	59.94	53.96
2M				
Total mass	1000.00	111.13[b]	1111.13	1000.00
DM	119.48	-2.37[c]	117.11	105.39
VS	102.04	-2.37[d]	99.67	89.70
N	5.03	-0.45[e]	4.58	4.12
P	1.39	no change	1.39	1.25
K	3.98	no change	3.98	3.58
C	58.89	-1.92[f]	56.97	51.27

[a] see Table 2.14
[b] Mass of water and straw added during storage minus DM loss. Composition of straw was not included due to very small impact.
[c] The change was calculated as sum of C and N losses.
[d] The same change as for DM (all DM loss was VS).
[e] Changes in total N were calculated as sum of N-emissions during the digestate storage: 0.440 kg NH_3-N + 0.027 kg N_2O-N + 0.000175 kg NO-N + 0.0112 kg N_2-N = 0.48 kg N
[f] changes in total C are calculated as a sum of C-losses due to CO_2 and CH_4 emissions during the digestate storage: (3.72 kg CO_2 * 12.011 g/mol/44.01 g/mol) + (1.68 kg CH_4 * 12.011 g/mol/16.04 g/mol) = 2.27 kg C.
[g] All the data is calculated per 1000 kg of digestate "ex-storage".

Use of synthetic and organic fertilizers-application to field

The digestate is considered to be spread on the field for fertilization with a slurry spreader. Since the digestate is planned to use for fertilization on maize in early growth stages and on renewed cultivated grasslands before plowing, it is possible to implement trailing hose spreaders (Vohu 2015).

The nutrient requirements of crops used for calculating the amounts of fertilizers to use for silage production are in accordance with the official fertilization recommendation standards (Table 2.21). In case of manure, the amount of spreading is regulated by Estonian law (RT I 1994,40,655) which limits the content of nitrogen (170 kg N /ha) and content of phosphorus per planning period (25 kg P/ ha). The same rules are suggested to apply for digestate spreading. So, the fertilization need calculations are based on the plant nutrient requirement, digestate nutrient content and manure nutrient availability for plants. The bioavailable proportion of N,P, K nutrients for plants in the digestate is estimated to be 70%, 60% and 90% accordingly (Pehme 2013). The emissions arising following digestate field application and the EFs used in the compilation of emission estimates from the implementation of synthetic fertilizers are presented in Table 2.22and Table 2.23.

Table 2.21 Plant nutrient needs (Kanger et al. 2014)

Crop	N (kg ha^{-1}) per year	P (kg ha^{-1}) per year	K (kg ha^{-1}) per year
Grass-clover mixture [14]	150	19	66
Perennial grasses	50	18	65
Maize	140	30	140

Table 2.22 Emissions from spreading biogas digestate to the field and from the use of inorganic fertilizers for 5Nm3 and 2Nm3 production units

Production Unit	5M	2M	Comments
Input	**value**	**value**	
Digestate "ex storage"	1000	1000	The process is related to the 1 000 kg digestate "ex storage", emissions are calculated relative to this.
Emission to air, kg per 1000 kg of digestate			
CH_4, kg	neglible	neglible	Assumed neglible in aerobic conditions
NH_3-N during application, kg	0.0079	0.0040	0.5% of TAN "ex-storage" (Hansen et al. 2008)TAN "ex-storage" is 72% of total N
NH_3-N in period after application, kg	0.2646	0.1339	12% of total N applied
N_2O-N (direct emissions), kg	0.0220	0.0112	IPCC guidelines, 0,01 kg N_2O-N per kg N applied
N_2O-N (indirect emissions), kg	0.0027	0.0014	Volatilization: IPCC guidelines, 0.01 kg N_2O-N per kg (NH_3-N+NO_x-N).
	0.0010	0.0005	

[14] Nutrient requirements of grass clover mixture are calculated assuming the mix consists of 25% of red clover and 75% of hay (Pehme 2013)

Production Unit	**5M**	**2M**	**Comments**
Input	**value**	**value**	
			Nitrate leaching: IPCC guidelines, 0.0075 kg N_2O-N per kg N.
NO_x-N, kg	0.00022	0.00011	NO_X–N = 0.1 * N_2O-N (direct)
N_2-N, kg	0.0661	0.0335	For sandy soil the N_2-N:N_2O-N ratio is 3:1 (Pehme 2013)
Discharge to water			
Nitrate leaching, kg N	0.0983	0.0497	6.37% of manure NH_4 based on model (Simmelsgaard & Djurhuus 1998): kg N * 0.7 * 6.37% (Pehme 2013)
Phosphate leaching, kg P	0.0108	0.0051	1.76% of manure P applied based on model (Ekholm et al. 2005; Pehme 2013)

Table 2.23 EFs used in the emission estimates arising from the application of synthetic fertilizers

Synthetic fertilizers	
NH_3, kg	0.037 kg NH_3/ kg N applied (Ammonium nitrate);and 0.113 kgNH_3/ kgN applied (Ammonium phosphate (MAP)) (EMEP & EEA 2013a)
N_2O-N (direct emissions), kg	IPCC guidelines, 0,01 kg N_2O-N per kg N applied
N_2O-N Indirect emissions, kg	Volatilization: IPCC guidelines, 0.01 kg N_2O-N per kg (NH_3-N+NO_x-N). Nitrate leaching: IPCC guidelines, 0.0075 kg N2O-N per kg N.
NO_x-N, kg	NO_X–N = 0.1 * N_2O-N (direct) (Pehme, 2013)
N_2-N, kg	For sandy soil the N_2-N:N_2O-N ratio is 3:1. (Pehme 2013)
Nitrate leaching, kg N	According to Kärblane (1998) the percentage of leached NH_3- N and NO_3-N from synthetic fertilizers equals to a ratio of 0.21/0.12 to the N leached (6.37%) from manure.
Phosphate leaching, kg P	According to Kärblane (1998) the percentage of leached P from synthetic fertilizers is equal to the P leached from applied manure, hence 1.76% P leaching was applied

Liming

As annual precipitation in Estonia exceeds evapotranspiration, calcium and magnesium carbonates leach out from the surface levels of soil, which in turn causes the lack of calcium and magnesium on over 22% of arable land and consequently acidification of the fields. To alleviate calcium-deficiency in field soils, quick-acting fine dusty limes are mainly used (NIR 2016). The EFs applied in the emission estimates of this LCI was 0.12 tons C/ (ton limestone or dolomite) and an estimated 3 t/ha would be applied over approximately 20% of arable land (Table 2.24).

Table 2.24 LCI data for liming

EF, tons C (ton limestone or dolomite)$^{-1}$	0.12	these are equivalent to carbonate carbon contents of the materials (12% for $CaCO_3$, 12.2% for $CaMg(CO_3)_2$) (IPCC 2006).
Lime applied, t/ha yr	3	(Vohu 2015)

3. RESULTS AND DISCUSSION

3.1 Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) was carried out using the EDIP 2003 methodology which is in line with the ISO 14044:2006 standard guidelines and by Talve and Põld (2005) found to be one of the most suitable methods for Estonian conditions to conduct an LCIA. For the sake of LCIA, a user-friendly, modular, easy-to-understand, life-cycle assessment tool that quantified energy consumption, fuel production, and air emissions and compare the environmental impacts of increased biomethane production with the base scenario in an Excel spreadsheet system was created.

The final results of the LCA of increased biomethane production and the avoided emissions from fossil fuel combustion and the crop production and manure management of the reference scenarios are presented in Table 3.1.

The results indicate that GHG emissions decrease in all the scenarios. The most favorable scenario considering GWP and taking into account the avoided emissions, would be the P2M scenario -112.6 kt CO_2 equivalent (eq). The respective emissions from the production of biomethane would be 303.17 ktCO_2 eq and the corresponding avoided emissions from the reference scenario -415.8 kt CO_2eq.

In terms of Acidification Potential (AP) the scenario that would accomplish most emission savings taking into account the avoided emissions would also be the P2M scenario where the total emissions concerning AP increase the slightest i.e. 0.7 ha per TWh fossil fuels replaced. Regarding Aquatic Eutrophication Potential (EP) the scenario that would accomplish most emission savings taking into account the avoided emissions would be the D2M scenario where concerning inland and marine water eutrophication a reduction in emissions would be -1.37 kt NO_3eq. However, the scenarios causing least environmental burden without taking into account the avoided emissions in AP impact category would be the scenarios where the replaced fossil fuel was petrol. In that case emissions from acidification were estimated to be 1.19 ha/ TWh for the 5M capacity production unit scenario. The smallest total EP was for the D5M scenario (5.15 kt NO_3eq/TWh).

Table 3.1 Environmental impacts of substituting 1 TWh of fossil fuels used by road transport

Scenario[10]	**Pr5M**	**Pr2M**	**P5M**	**P2M**	**D5M**	**D2M**
Global warming Potential, kt CO_2eq						
CO_2eq balance	-57.21	-79.14	-94.03	**-112.60**	-40.15	-63.32
Avoided emissions	-332.49	-439.60	-325.57	-415.77	-336.34	-451.91
Total emissions	275.29	360.46	231.53	303.17	296.19	388.58
Acidification Potential, ha UES						
Balance	0.86	0.74	0.80	**0.70**	0.89	0.77
Avoided emissions	-0.55	-2.01	-0.39	-1.62	-0.62	-2.19
Total emissions	1.41	2.75	1.19	2.32	1.52	2.96
Eutrophication Potential, kt NO_3eq						
Balance	3.62	-1.11	2.93	-0.49	2.99	**-1.37**
Avoided emissions	-2.49	-10.29	-2.22	-8.22	-3.58	-11.26
Total emissions	6.10	9.18	5.15	7.73	6.57	9.89

3.1.1 Global Warming Potential

The largest contributor to the avoided emissions in all the six fossil fuel replacement scenarios would be the combustion of petrol and diesel fuels (Figure 3.1 and Table 3.2) (Pr:-260.5 ktCO_2eq, P:-264.7 kt CO_2eq, D:-258.8 kt CO_2eq). However, the GHG emissions from the entire biogas production chain would be the smallest for the petrol substitution scenarios as were expected (Pr5M: 275.3 kt CO_2eq, Pr2M:360.5 kt CO_2eq; P2M:231.5 kt CO_2eq, P5M: 303.2 kt CO_2eq; D5M: 296.2 ktCO_2eq, D2M: 388.6 kt CO_2eq), whereas the volume of biomethane for the 1 TWh of petrol replaced with biomethane was assumed to be the lowest. Hence, the least amount of resources for biogas production purposes would have to be exploited exposing thereby lowest burden to the environment. The larger production units show a negative effect in terms of net emission savings to the total emissions in all the scenarios which results from the composition of AD substrates used in the corresponding scenarios, although emissions from biogas production are higher for 2M units. The emissions from the biogas production in the 2M scenario are elevated by the larger quantities of manure used as a substrate for AD form larger quantities of leftover residues in the form of digestate and consequently more emissions arise from its outside storage (Pr2M: 166.5 kt CO_2eq; P2M: 140.5 kt CO_2eq, D2M: 179.5 kt CO_2eq) than from 5M production units (Pr5M: 85.6 kt CO_2eq, P5M: 72.4 kt CO_2eq; D5M: 92.1 kt CO_2eq), where mainly silage substrates are used. The emissions are balanced in favor of the 2M scenarios by the negative manure storage emissions from the reference scenario (Pr5M: -22.3 kt CO_2eq, Pr2M: -110.0 kt CO_2eq; P2M: -18.9 kt CO_2eq, P5M: -92.8 kt CO_2eq; D5M: -24.1 kt CO_2eq, D2M:-118.6 kt CO_2eq)

Another common feature of the 2M production unit scenarios are the larger emission savings from crop production (Pr2M: -69.1 kt CO_2eq; P2M: -58.3 kt CO_2eq, D2M: -74.5 kt CO_2eq) compared to the 5M scenarios (Pr5M: -49.6 kt CO_2eq, P5M: -42.0 kt CO_2eq; D5M: 53.4 kt CO_2eq,), which would result of the improvement in existing management of crop residues on the agricultural lands. 2M scenarios assumed higher grassland silage use and the practice of leaving the grass residues on the fields or to the edges of the field to decay after harvesting and crushing, thereby delivering higher N_2O reference emissions in comparison to the scenarios where the harvested silage is used purposefully (Vohu 2015). Compared to the reference scenario, there is an improvement concerning manure management, mainly due to avoided CH_4 emissions via anaerobic digestion.

Table 3.2 Results of the GWP assessment, kt CO_2eq

Scenario[10]	**Pr5M**	**Pr2M**	**P5M**	**P2M**	**D5M**	**D2M**
Additional fuels	39.0	37.9	32.5	31.7	41.5	40.6
Animal housing	2.4	11.9	2.1	10.1	2.6	12.9
Fertilization (digestate and inorganic fertilizers and liming)	77.7	72.5	64.8	60.4	83.9	78.3
Biogas production	35.4	36.4	30.0	30.7	38.1	39.2
Avoided fossil fuels	-260.5	-260.5	-264.7	-264.7	-258.8	-258.8
Crop production	35.2	35.3	29.8	29.8	37.9	38.1
Outdoor storage of the digestate	85.6	166.5	72.4	140.5	92.1	179.5
Crop production (reference scenario)	-49.6	-69.1	-42.0	-58.3	-53.4	-74.5
Manure management (reference scenario)	-22.3	-110.0	-18.9	-92.8	-24.1	-118.6
Total avoided emissions	-332.5	-439.6	-325.6	-415.8	-336.3	-451.9
Total emissions biogas production	275.3	360.5	231.5	303.2	296.2	388.6
Net balance	-57.2	-79.1	-94.0	-112.6	-40.2	-63.3

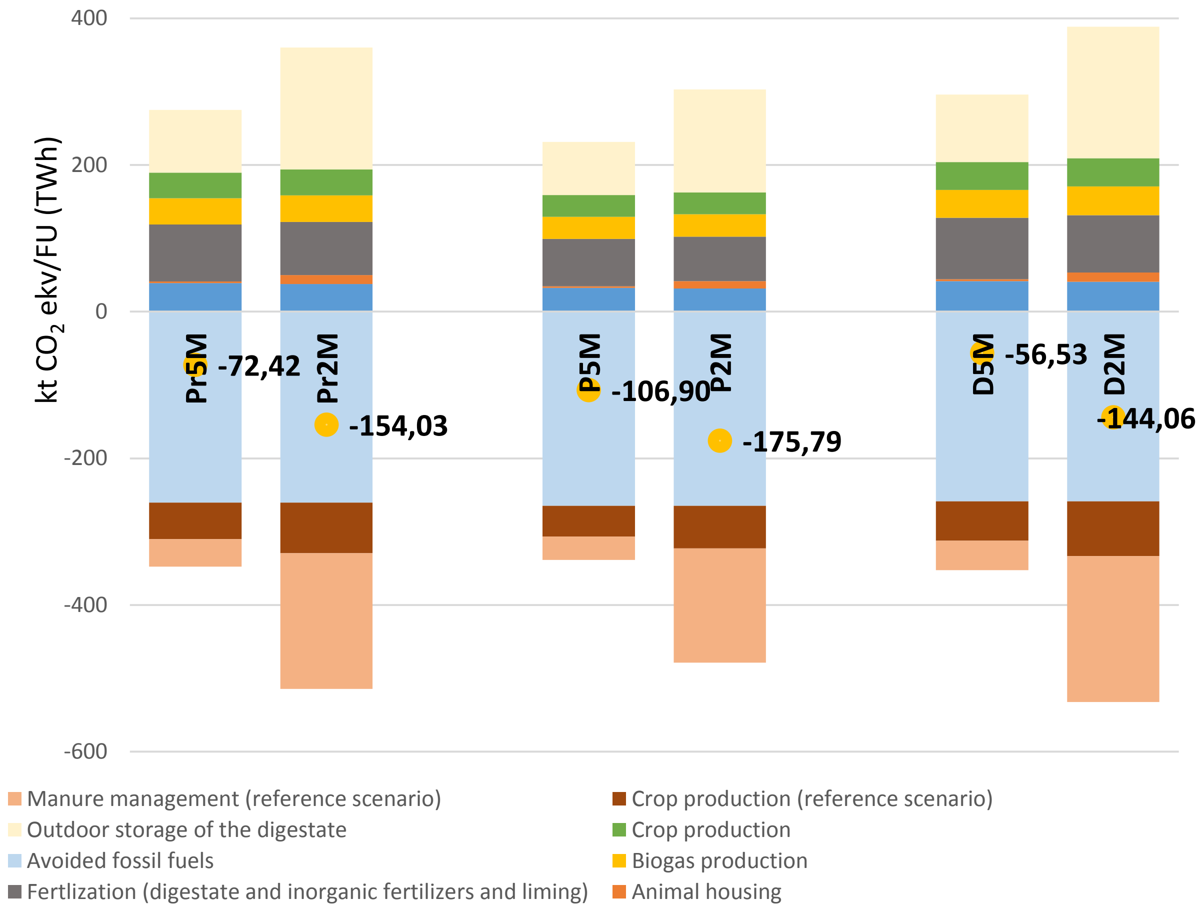

Figure 3.1 Results of the assessment of GWP in biomethane production and in the reference scenarios, kt CO_2eq/ FU (TWh)

3.1.2 Aquatic Eutrophication Potential

The results of this LCA indicated a reduction in terms of aquatic EP in 2M scenarios: -1.11 kt NO_3eq in the proportional, - 0.49 kt NO_3eq in the petrol and -1.37 kt NO_3eq in the diesel scenario. An increase of EP is observed in the 5M proportional, petrol and diesel scenarios: 3.62 kt NO_3eq, 2.93kt NO_3eq and 2.99 kt NO_3eq respectively.

As it is seen from the Table 3.3and Figure 3.2 the main contributors to the considerable increase in EP in all the biomethane scenarios are the emissions (Pr5M: 3,35 kt NO_3eq, Pr2M: 3,23 kt NO_3eq, P5M: 2,83 kt NO_3eq, P2M: 2,72 kt NO_3eq, D5M: 3,61 kt NO_3eq, D2M: 3,49 kt NO_3eq) caused by increased fertilizer use (both inorganic and organic) due to increased crop production.

The major reason why the 5M scenarios show a slight increase in net emissions (Pr5M: 1.33 kt NO_3eq, Pr2M: 2.59 kt NO_3eq, P5M:1.12 kt NO_3eq, P2M: 2.19 kt NO_3eq, D5M: 1.43kt NO_3eq, D2M:2.80 kt NO_3eq), are the emissions added to the net balance by largely silage origin digestate storage. The digestate in 2M scenarios consists mainly of anaerobically digested manure and the emissions arising from the digestate storage are compared to the avoided emissions from reference scenario manure storage. The EFs used in emission estimations for dairy slurry and silage/manure digestate, are the same to a large extent. Additionally, the quantities of fertilizers used are proportionally larger for the 5M scenarios than in case of 2M scenarios.

Table 3.3 Results of the EP category assessment, kt NO_3eq/FU (TWh)

Scenario[10]	**Pr5M**	**Pr2M**	**P5M**	**P2M**	**D5M**	**D2M**
Additional fuels	0.75	0.75	0.63	0.62	0.80	0.80
Animal housing emissions	0.49	2.43	0.42	2.05	0.53	2.62
Outdoor storageof the digestate	1.33	2.59	1.12	2.19	1.43	2.80
Fertilization (inorganic, organic fertilizers)	3.35	3.23	2.83	2.72	3.61	3.49
Avoided fossil fuels	-1.12	-1.12	-0.49	-0.49	-1.38	-1.38
Crop residues	0.18	0.18	0.15	0.15	0.19	0.19
Crop residues (reference)	-0.25	-0.35	-0.21	-0.30	-0.27	-0.38
Manure management (reference)	-1.11	-8.81	-1.51	-7.44	-1.93	-9.50
Net balance	3.62	-1.11	2.93	-0.49	2.99	-1.37
Total avoided emissions	-2.49	-10.29	-2.22	-8.22	-3.58	-11.26
Total emissions biogas production	6.10	9.18	5.15	7.73	6.57	9.89

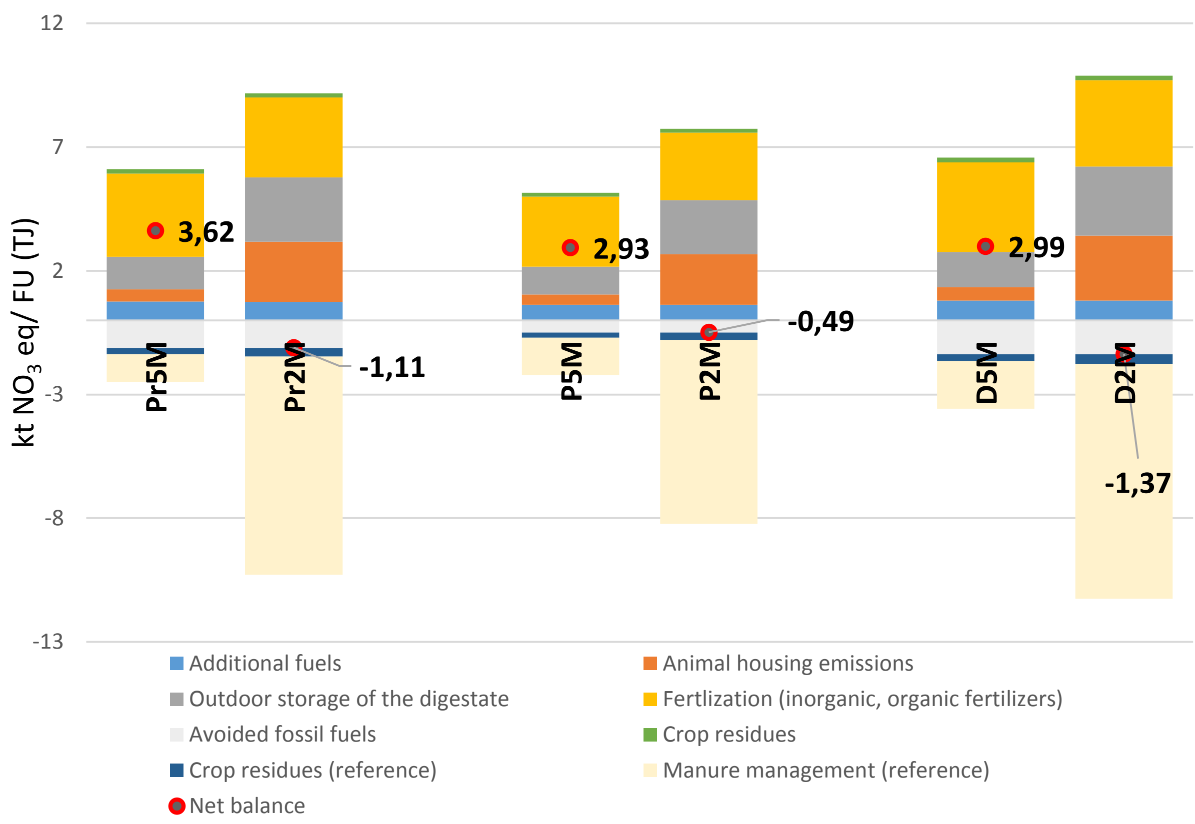

Figure 3.2 Results of the assessment of EP in biomethane production and in the reference scenarios kt NO_3eq/ FU (TWh)

3.1.3 Acidification Potential

The results of this LCA show a rise in AP in all the scenarios. In detail, for the 2M scenarios: 0.73 ha in the proportional, 0.68 ha in the petrol and 0.75 ha in the diesel scenario. A growth in AP as was for the EP occurs in the 5M proportional, petrol and diesel scenarios: 0.84 ha, 0.79 ha and 0.88 ha accordingly (Table 3.4 and Figure 3.3).

The final results of the acidification impact category are influenced by the increased SO_2 emissions as a result the production of electrical energy of oil shale for the biogas production and refining operations. Additionally, the impact category is largely contributed by the same enhanced agricultural activities described under GWP and EP impact categories.

Table 3.4 Results of the AP category assessment, ha UES/FU (TWh)

Scenario[10]	Pr5M	Pr2M	P5M	P2M	D5M	D2M
Additional fuels	0.15	0.15	0.13	0.13	0.16	0.16
Animal housing emissions	0.21	1.04	0.18	0.88	0.23	1.12
Outdoor storage of the digestate	0.53	1.04	0.45	0.88	0.57	1.12
Fertilization (inorganic, organic fertilizers and liming)	0.50	0.50	0.42	0.43	0.54	0.54

Scenario[10]	Pr5M	Pr2M	P5M	P2M	D5M	D2M
Avoided fossil fuels	-0.18	-0.18	-0.08	-0.08	-0.22	-0.22
Manure management (reference)	-0.37	-1.83	-0.31	-1.54	-0.40	-1.97
Net balance	0.84	0.73	0.79	0.68	0.88	0.75
Total avoided emissions	-0.55	-2.01	-0.39	-1.62	-0.62	-2.19
Total emissions biogas production	1.40	2.73	1.18	2.31	1.50	2.95

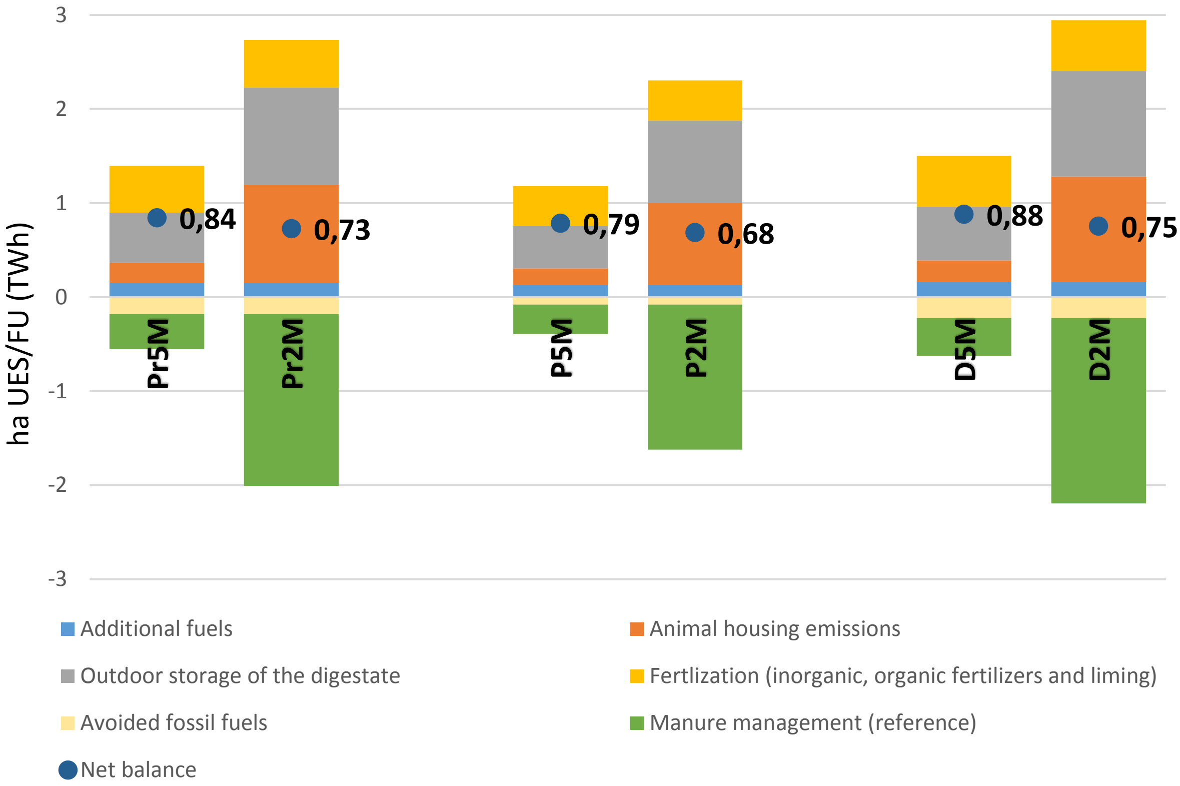

Figure 3.3 Results of the LCIA in the AP impact category, representing the results of biomethane production and the reference scenarios, ha UES/ FU (TWh)

3.1.4 Sensitivity analysis

Sensitivity analysis helps to give a sense of the proportional importance of different entry data on the results of the modelling (FAO 2010). It is also relevant in the present LCA, since subjective methodological choices had to be made occasionally, out of the necessity of essential data and the difficulties obtaining it, which compelled the use of several simplifications and assumptions. In order to complete the sensitivity analysis, the effect of certain parameters were tested by changing one parameter at a time, while holding the other parameters at constant levels.

The sensitivity analysis was conducted changing the following parameters:

1. It was assumed that CH_4 losses from the biogas production chain yield to 4%.
2. It was assumed that CH_4 losses from the biogas production are lower than in the main scenarios and decreased to 1%.
3. It was assumed that the digestate storage facility is covered with impermeable cover.

CH_4 losses during the production chain of biogas is one parameter frequently tested in other LCAs about biogas production (Pehme 2013; Buratti et al. 2013).

The results of modelling the CH_4 losses presented in Table 3.15 indicate the apparent sensitivity of the examined systems to possible CH_4 slips during the production and transit of the final product. A threshold exists after what the production of biomethane is not feasible, considering the primary aim being to achieve emission savings. For example, with a 4% CH_4 slip (Figure 3.4; Figure 3.5), GHG emissions would surge and yield in total net emission increase in three of the examined scenarios: +0.5% in 5M Proportional and 2M Diesel scenario and +7% in 5M Diesel scenario compared to the reference scenario. The emissions of the diesel scenario were more vulnerable to the CH_4 modelling, since the differences in the GWP of diesel and petrol combustion were caused by the EFs used for estimating CH_4 emissions from road transport (2.02 t/ TJ for diesel and 12.16 t/TJ for petrol (NIR 2016), 0.0092 t/TJ for biomethane (IPCC 2006c).

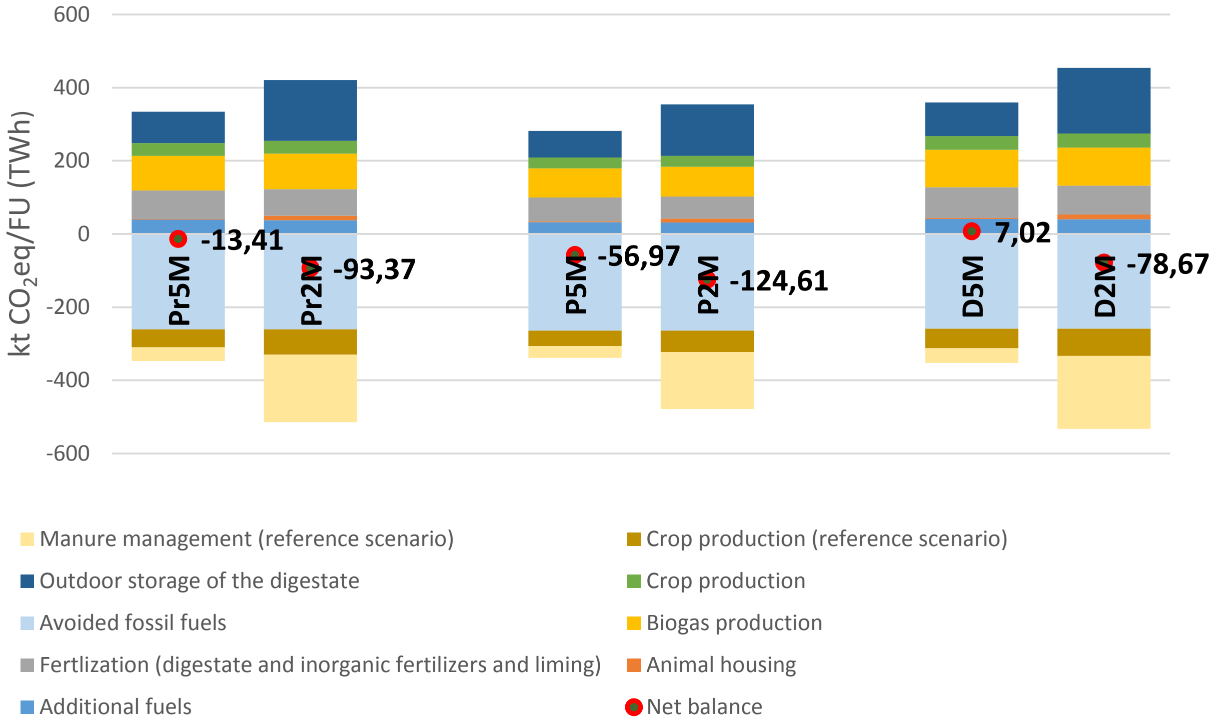

Figure 3.4 GWP assessment assuming CH_4 losses 4%, kt CO2eq/ FU (TWh)

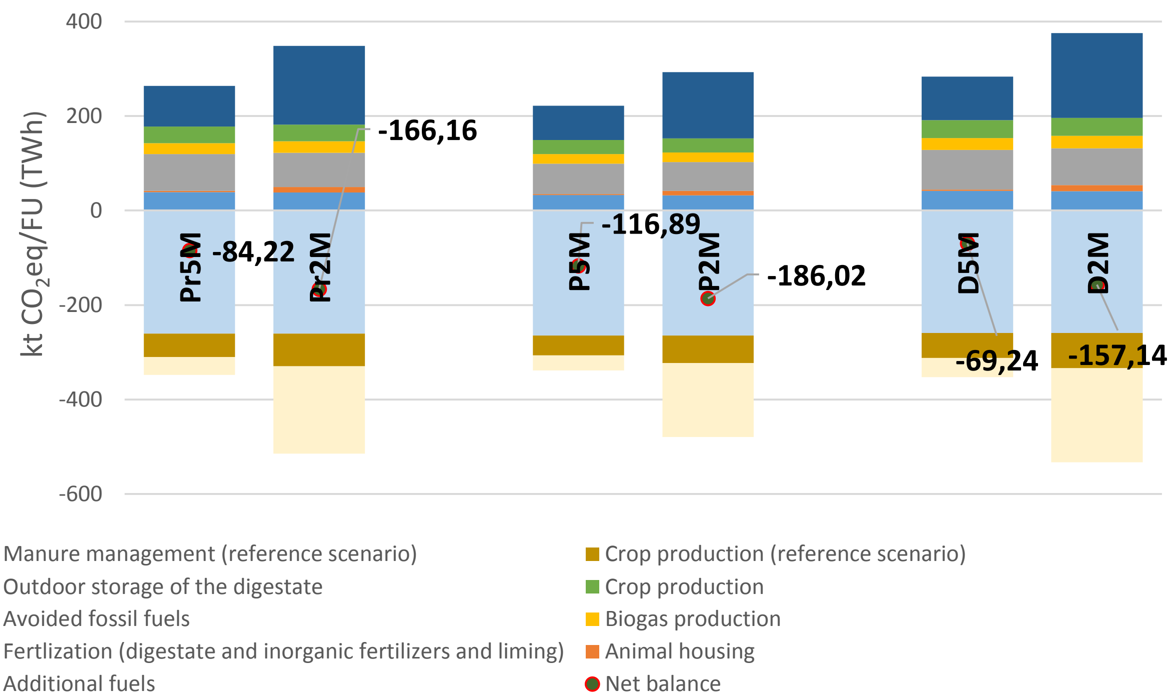

Figure 3.5 GWP assessment assuming CH_4 losses 1%, kt CO_2eq/ FU (TWh)

Covering manure storages with impermeable covers has been proven to be an effective mitigation practice of GHG, if the captured CH_4 is burned in a flare or used to produce electricity. If the captured CH_4 is not utilized, it will become an explosion hazard and/or tear the cover. As a result, the fraction of compounds in the gas phase decrease and that trapped in liquid, increase by the elevated air pressure inside the storage. Under these circumstances, at the stage of the organic fertilizer removal the gas trapped in the liquid is also freed and burning or combusting the collected CH_4 beforehand should be the most desirable option (Nicolai & Pohl 2004; Montes et al. 2013). The use of impermeable covers (Figure 3.6) makes it also possible to control NH_3 emissions, with an almost 100% reduction in emissions compared to an uncovered storage facility (EMEP & EEA 2013b). However, caution should be exercised, as it is likely for field emissions to increase resulting from the higher concentration of gases trapped inside the digestate (Anderson-Glenna & Morken 2013).

Figure 3.6 Covered digestate storage tank (reproduced from Lukehurst, Frost, & Seadi, 2010)

The results of the sensitivity analysis are encouraging towards the use of impermeable cover during the digestate storage. The emission savings increase more than twofold in some scenarios for all the impact categories. The GWP emissions in 2M, 5M proportional, petrol and diesel scenarios (Figure 3.7) are respectively -43%, -55%, -51%, -60%, -39% and -53% smaller compared to the reference scenario (see Table 3.5 for comparison).

The EP emissions decreased in proportional, petrol and diesel 2M scenarios compared to the reference scenario by -24%, -20% and -25%, but were still higher in the 5M biogas production scenarios with respect to the reference scenario. Although, the emissions in this sensitivity analysis were reduced in the AP impact category, the total net emissions were still considerably higher parallel to the reference scenario.

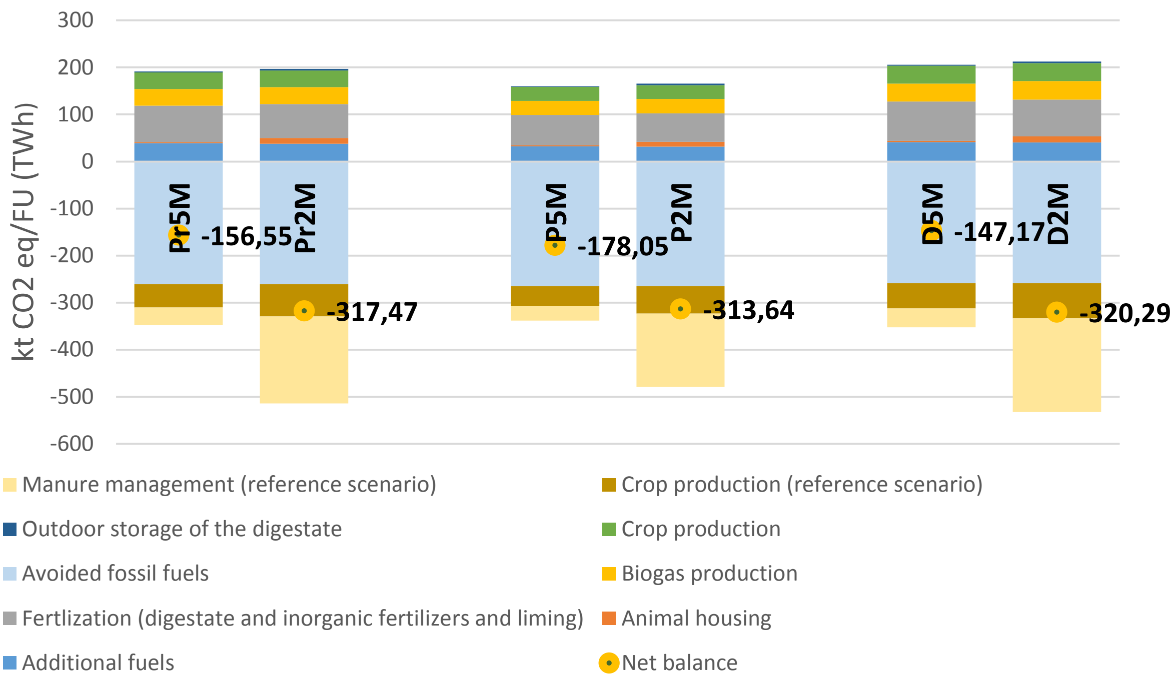

Figure 3.7 GWP assessment assuming an impermeable cover on the digestate storage facility, kt CO_2eq/ FU (TWh)

Table 3.5 Reduction in emissions compared to the reference scenario emissions, %

Scenario[10]	**Pr5M**	**Pr2M**	**P5M**	**P2M**	**D5M**	**D2M**
Global Warming Potential						
CH_4 loss 1.5%	-17%	-18%	-29%	-27%	-12%	-14%
Sensitivity analysis: CH_4 loss 4%	+0,5%	-4%	-14%	-15%	+7%	+0,5%
Sensitivity analysis: CH_4 loss 1%	-21%	-21%	-32%	-30%	-16%	-17%
Sensitivity analysis: digestate storage with impermeable cover	-43%	-55%	-51%	-60%	-39%	-53%
Eutrophication Potential						
CH_4 loss 1.5%	145%	-11%	132%	-6%	84%	-12%
Sensitivity analysis: digestate storage with impermeable cover	117%	-24%	105%	-20%	62%	-25%
Acidification Potential						
CH_4 loss 1.5%	155%	37%	203%	43%	143%	35%

Scenario[10]	**Pr5M**	**Pr2M**	**P5M**	**P2M**	**D5M**	**D2M**
Sensitivity analysis: digestate storage with impermeable cover	109%	12%	148%	17%	100%	10%

4. CONCLUSIONS

The results of the current master's thesis showed a reduction in GHG emissions for all the scenarios. The most favorable scenario considering GWP and AP would be the P2M scenario and where the main substrates used for anaerobic digestion were manure and natural grass. In terms of EP, the scenario that showed the smallest increase in emissions was the D2M scenario with co-digestion of manure and natural grass.

It can be concluded from the conducted LCA, that enhanced tillage activity rooting from the increased biogas production, may cause a considerable added burden to the environment from a life cycle perspective and possibly even out the potential reduction in emissions contributed by the decreased use of fossil fuels by road transport. The results of the current master's thesis thereby suggest that an emphasis should be placed on sustainable agricultural practices, as the remaining digestate fertilizer, if used without proper abatement measures, may pose a considerable threat to the environment and add to the AP, EP and to the GWP.

Another prominent factor that has shown to influence GHG emissions are land use change related, which have not been considered in this LCA, as it is not clear what land would be used if any of these scenarios should be put into practice. Nevertheless, this should remain under consideration for future reference as it is proven to have a relevant impact to the overall emission balance in other similar studies (Pehme 2013; Hamelin et al. 2014a).

The economic analysis of the same scenarios implicated the most favorable to be the ones where petrol would be the replaced fossil fuel and biomethane produced in large 5M production units (Vohu 2015). However, the 2M scenarios showed better results in all the environmental impact assessment categories, which imply to the improvement of existing agricultural residues management compared to the 5M scenarios, where the emissions were proportionally higher due to mainly silage residue digestate storage. Hence, the decision makers and other interested parties, may consider the choice of substrates used in the 2M scenarios, when determining the optimum scenario for biomethane production taking into account both economic and environmental conditions.

The results of the sensitivity analysis of the CH_4 losses during biomethane production, indicated a threshold after which the emissions from production of biomethane outweigh potential emission savings and promising emission savings from implementation of impermeable covers over the digestate storage facilities.

The main conclusion drawn from the current master's thesis is that harnessing biogas from manure, natural grass and maize silage could under certain circumstances be considered a feasible option from an environmental protection standpoint to fulfill the national renewable targets. However, a precondition of realization these scenarios should be a sustainable approach while taking necessary precautions to avoid environmental and societal problem shifting from one life cycle stage to another.

RÉSUMÉ

Estonia's biomethane potential is evaluated to be around 450 million Nm^3, of which grass biomass accounts for over 80%. This distribution of resources is explained by the fact that only a mere one-third of the theoretical total yield of Estonia's grass biomass is used purposefully, while 1.4 million tons in dry weight is unapplied every year. According to the research by Vohu (2015) in case 9.5% of Estonia's aggregate petrol and diesel fuel consumption were replaced by biomethane, the required amount of biomethane would be 109-139 million Nm^3, depending on the fuel type replaced. The EU Directive 2009/28/EC (adopted in 2009) on the promotion of the use of energy from renewable sources (RED) holds a mandatory minimum target for the use of fuels produced using renewable energy sources and according to RED should constitute 10% of the total consumption of petrol and diesel fuel in transport by 2020 in each member state.

The existing studies (Pehme 2013; Heinsoo et al. 2010; Melts 2014) carried out in Estonia on environmental impacts of biogas production, have generally drawn positive conclusions about using unutilized biomass from natural grasslands. An LCA of co-digestion with natural grass and dairy slurry conducted by Sirli Pehme, indicated significantly lower contribution to impact category GWP, but increased emissions for EP and AP impact categories compared to the reference scenario. The study also suggested that energy grass should only be used as a substrate for AD in case the land used for producing the grass could not be cultivated for other (food or feed) purposes (e.g. using fields where conditions are not suitable for feed/food production) (Pehme 2013).

The goal of the current master's thesis was to assess alternative biogas processing routes and single out the most favorable scenario in terms of environmental gain. The analysis using a life-cycle approach was carried out based on the scenarios created within in the master's thesis of Vohu (2015). The latter study aimed to evaluate economic impacts in case of reduction of petrol and diesel fuel consumption as a vehicle fuel and their replacement with biomethane. Simultaneously, an LCA for the entire production chain enabled to pinpoint the main contributing unit processes to the emission flows. To execute the goal of the current master's thesis an LCA was conducted following the guidelines set in the ISO 14044:2006 standard.

The results of the current master's thesis showed a reduction in GHG emissions for all the scenarios. The most favorable scenarios considering Global Warming Potential, Aquatic Eutrophication and Acidification Potential impact categories, would be the scenarios where

mainly manure substrates with smaller additions of grass silage were used for biogas production. For Global Warming Potential the largest contributor to the avoided emissions in all the six fossil fuel replacement scenarios would be the combustion of petrol and diesel fuels. The emissions from the biogas production are elevated in all impact categories mainly by the digestate storage and field application, at the same time, the net emissions are smaller for the scenarios with higher emissions from avoided manure storage. Concerning Global Warming Potential and compared to the reference scenario, there would be an improvement concerning manure management, mainly due to avoided CH_4 emissions via anaerobic digestion.

The main contributors to the considerable increase in Acidification and Eutrophication Potential in all the biomethane scenarios were the emissions caused by increased fertilizer use (both inorganic and organic) due to increased crop production and the outside storage of the digestate. The results of the Acidification Potential impact category were also influenced by the increased SO_2 emissions as a result of the production of electrical energy from oil shale for biogas production and refining operations.

The results of the sensitivity analysis of the CH_4 losses during biomethane production, indicated a threshold after which the emissions from production of biomethane outweigh potential emission savings and promising emission savings from implementation of impermeable covers over the digestate storage facilities.

The main conclusion drawn from the current master’s thesis is that harnessing biogas from manure, natural grass and maize silage could under some circumstances be considered a feasible option from an environmental protection standpoint to fulfill the national renewable targets. However, a precondition for realizing these scenarios should be a sustainable approach while taking necessary precautions to avoid problem shifting from one life cycle stage to another.

RESÜMEE

Eesti biometaani potentsiaali suuruseks on hinnatud ligikaudu 450 miljonit Nm^3, millest rohtne biomass moodustab üle 80%. Vastavalt Vohu (2015) koostatud magistritöö tulemustele oleks 9,5% Eesti bensiini ja diisli mootorkütuse tarbimise asendamiseks sõltuvalt kütuseliigist vaja toota 109-139 miljonit Nm^3 biometaani. Euroopa Liidu direktiivis 2009/28 / EÜ (vastu võetud 2009) taastuvatest energiaallikatest toodetud energia kasutamise edendamise kohta alusel, peab aastaks 2020 igas liikmesriigis 10 % transpordikütusest pärinema taastuvatest energiaallikatest.

Eestis seni läbiviidud uuringud biogaasi tootmise keskkonnamõjude kohta (Pehme 2013; Heinsoo jt. 2010; Melts 2014) on üldjuhul näidanud positiivseid tulemusi rohumaade kasutamata biomassi ja sõnniku rakendamisel biogaasi tootmiseks. Pehme (2013) olelusringi hindamise tulemused looduslike rohumaade silo ja piimalehmade läga kooskääritamise kohta näitasid olulist heitkoguste vähenemist globaalse soojenemise mõjukategoorias, ent võrrelduna referents-stsenaariumiga suurenesid heitkogused eutrofeerumise ja hapestumise mõjukategooriates (Pehme 2013).

Käesoleva magistritöö eesmärgiks oli hinnata Vohu (2015) magistritöö raames modelleeritud biogaasi tootmise stsenaariumeid keskkonnamõjude aspektist, kasutades olelusringipõhist lähenemist. Vohu (2015) uurimistöö ülesandeks oli hinnata fossiilsete mootorkütuste osalise asendamisel biometaaniga ja selle tootmisel kaasnevaid majandusmõjusid. Käesoleva magistritöö olelusringi hindamine viidi läbi vastavalt ISO 14044: 2006 standardile.

Kõige paremaid tulemusi näitasid kõikides mõjukategooriates stsenaariumid, milles peamisteks anaeroobsel kääritamisel kasutatavateks substraatideks oli ülekaalus sõnnik ja lisandiks rohumaade silo. Hapestumise mõjukategooria heitkogused kasvasid kõigis stsenaariumites, ent väikseim heitkoguste suurenemine toimus stsenaariumis, milles asendatavaks kütuseks oli bensiin. Arvestades globaalse soojenemise potentsiaali, näitasid kõige soodsamaid tulemusi stsenaariumid, kus asendatavaks kütuseks oli samuti bensiin ja eutrofeerumise potentsiaali puhul oli keskkonna seisukohalt parim, kui asendatavaks kütuseks oli diisel.

Magistritöö peamine järeldus on, et biogaasi tootmine sõnnikust, rohumaade ja maisi silost võib teatud tingimustel olla keskkonnakaitse seisukohalt õigustatud, et täita riiklikke taastuvenergia eesmärke. Seejuures aga peaks stsenaariumite rakendamine toimuma jätkusuutlikult, vältimaks keskkonna ja ühiskondlike probleemide nihkumist ühest olelusringi etapist teise.

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